

Constraints on Ceres' internal structure from the Dawn gravity and shape data

Caltech Yuk Yung Seminar

21 February 2017

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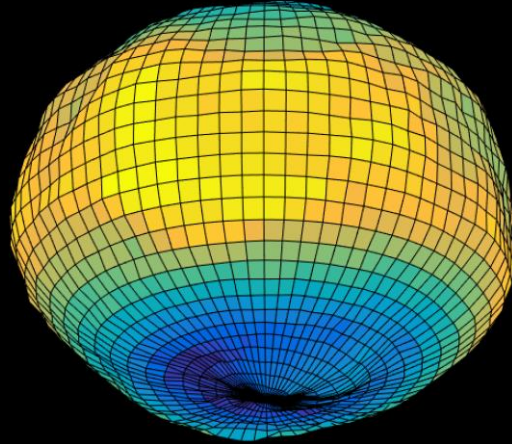


EAPS
Earth, Atmospheric and Planetary Sciences

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

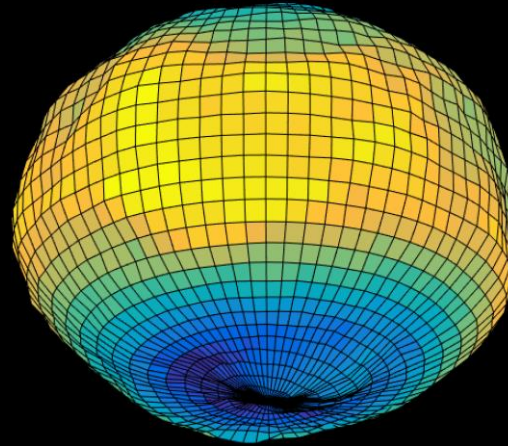
Shape models

➤ Geographic grid

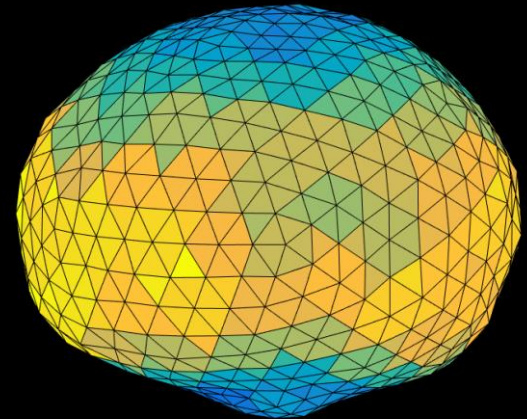


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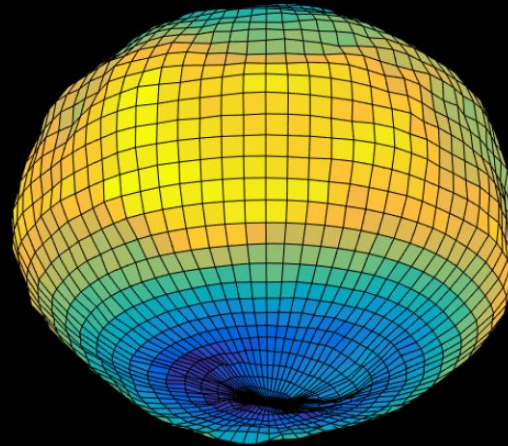


➤ Polyhedral model

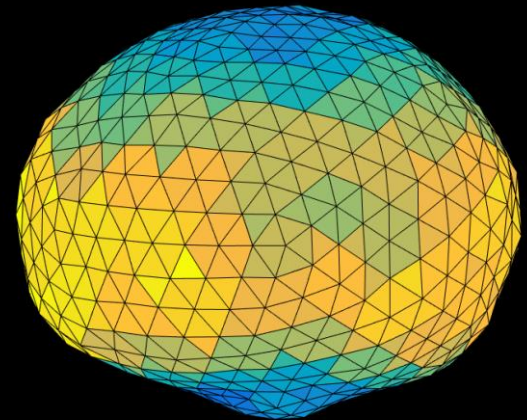


Shape models

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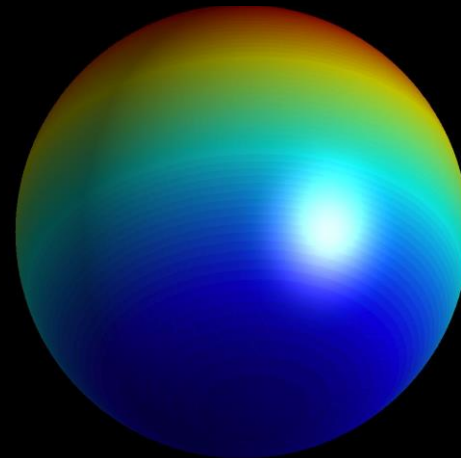


➤ Polyhedral model



➤ Spherical harmonic expansion

- set of orthogonal functions on a sphere



Gravity models

- Spherical harmonics

$$U(r, \varphi, \lambda) = \frac{GM}{r} \left[1 + \sum_{n=2}^{\infty} \left(\frac{R_0}{r} \right)^n \left(C_{nm} \cos(m\lambda) + S_{nm} \sin(m\lambda) \right) P_n(\sin \varphi) \right]$$

U – gravitational potential

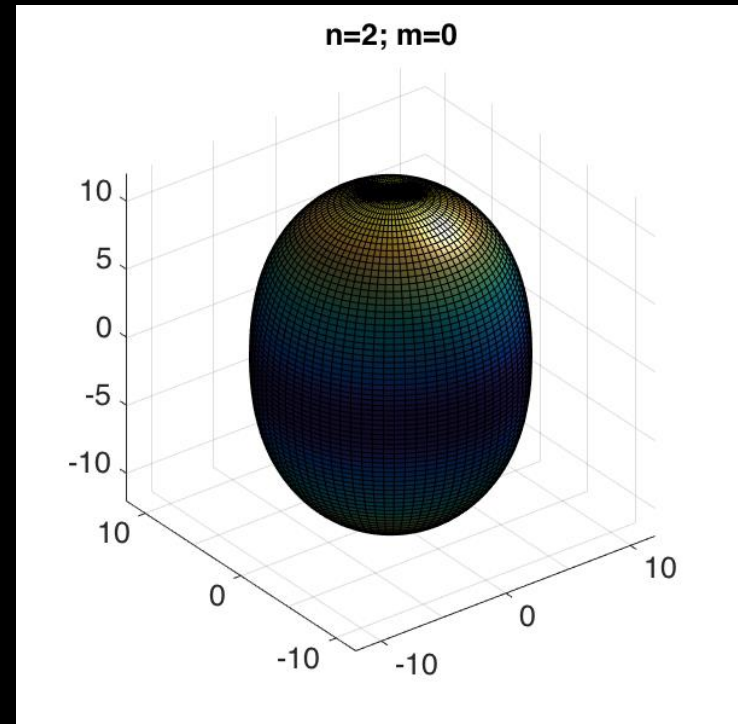
φ – latitude

λ – longitude

r – radial distance

n – degree

m – order



Gravity models

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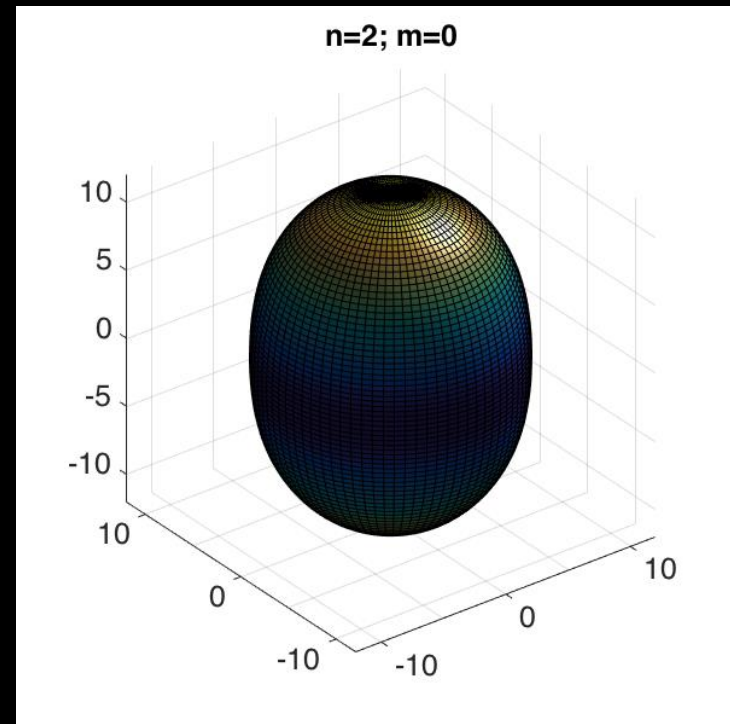
λ – longitude

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n – degree

m – order

- Ellipsoidal harmonics
- Mascons



Gravity and topography in spherical harmonics

- Shape radius vector

$$r(f, l) = R_0 \sum_{n=1}^{\infty} \sum_{m=0}^n (A_{nm} \cos(m l) + B_{nm} \sin(m l)) P_{nm}(\sin f)$$

- Gravitational potential

$$U(r, f, l) = \frac{GM}{R} + \sum_{n=2}^{\infty} \sum_{m=0}^n \frac{R_0^n}{r^{n+1}} (C_{nm} \cos(m l) + S_{nm} \sin(m l)) P_{nm}(\sin f)$$

- Power Spectral Density

$$S_n^{gg} = \sum_{m=0}^n \frac{C_{nm}^2 + S_{nm}^2}{2n+1}$$

gravity

$$S_n^{tt} = \sum_{m=0}^n \frac{A_{nm}^2 + B_{nm}^2}{2n+1}$$

topography

$$S_n^{gt} = \sum_{m=0}^n \frac{A_{nm} C_{nm} + B_{nm} S_{nm}}{2n+1}$$

gravity-topography
cross power

Hydrostatic equilibrium

- **In hydrostatic equilibrium**
 - Surfaces of constant density, pressure and potential coincide
 - No shear stresses

Hydrostatic equilibrium

➤ **In** hydrostatic equilibrium

Hydrostatic equilibrium

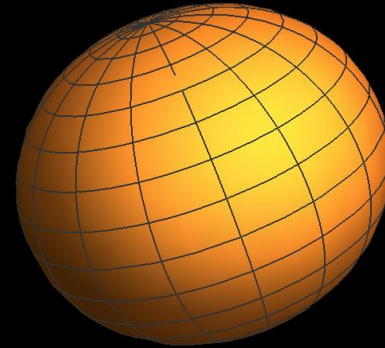
➤ In hydrostatic equilibrium

$$\rho = \rho(r), \omega$$

Hydrostatic equilibrium

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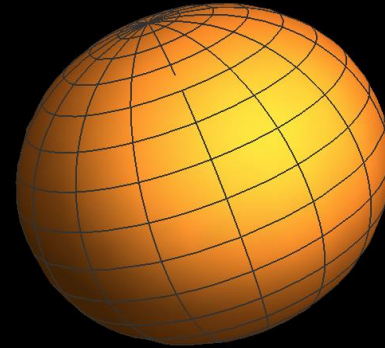
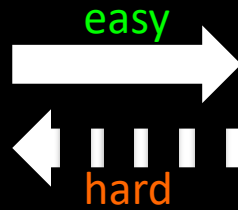
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Hydrostatic equilibrium

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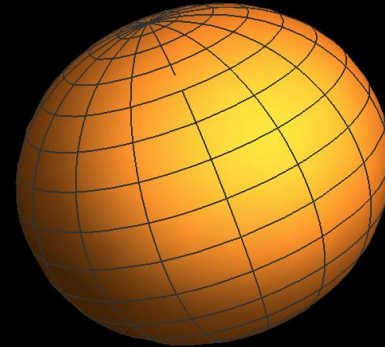
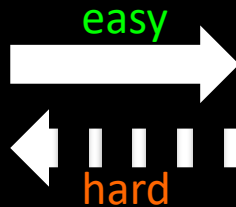
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Hydrostatic equilibrium

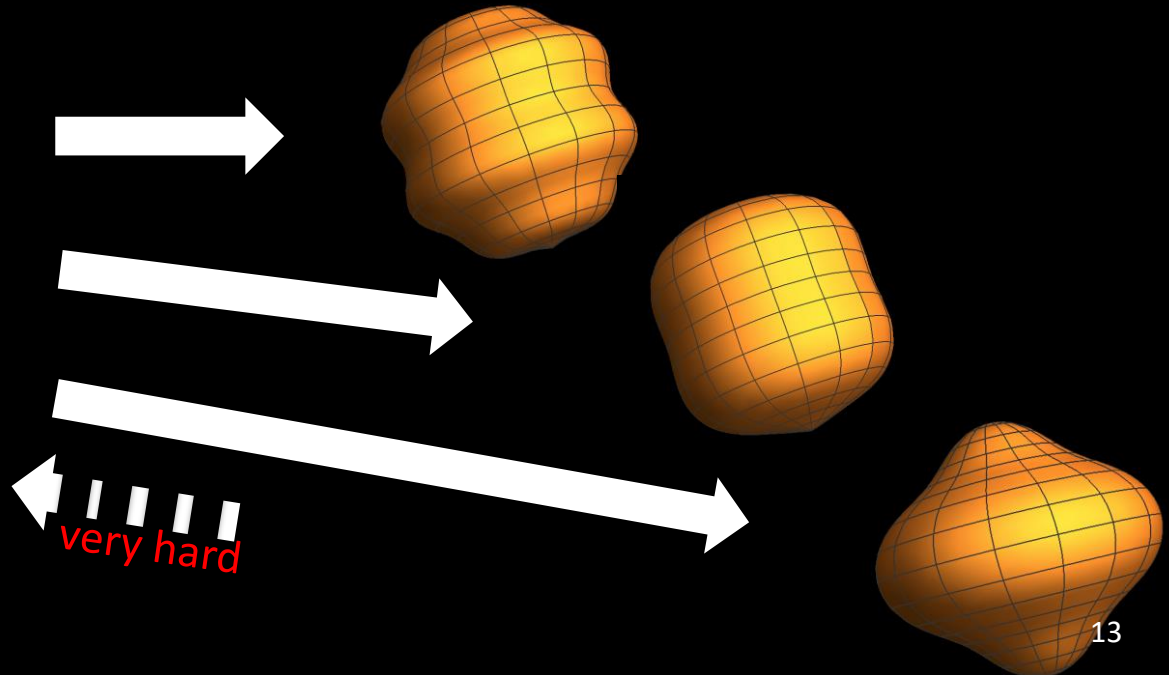
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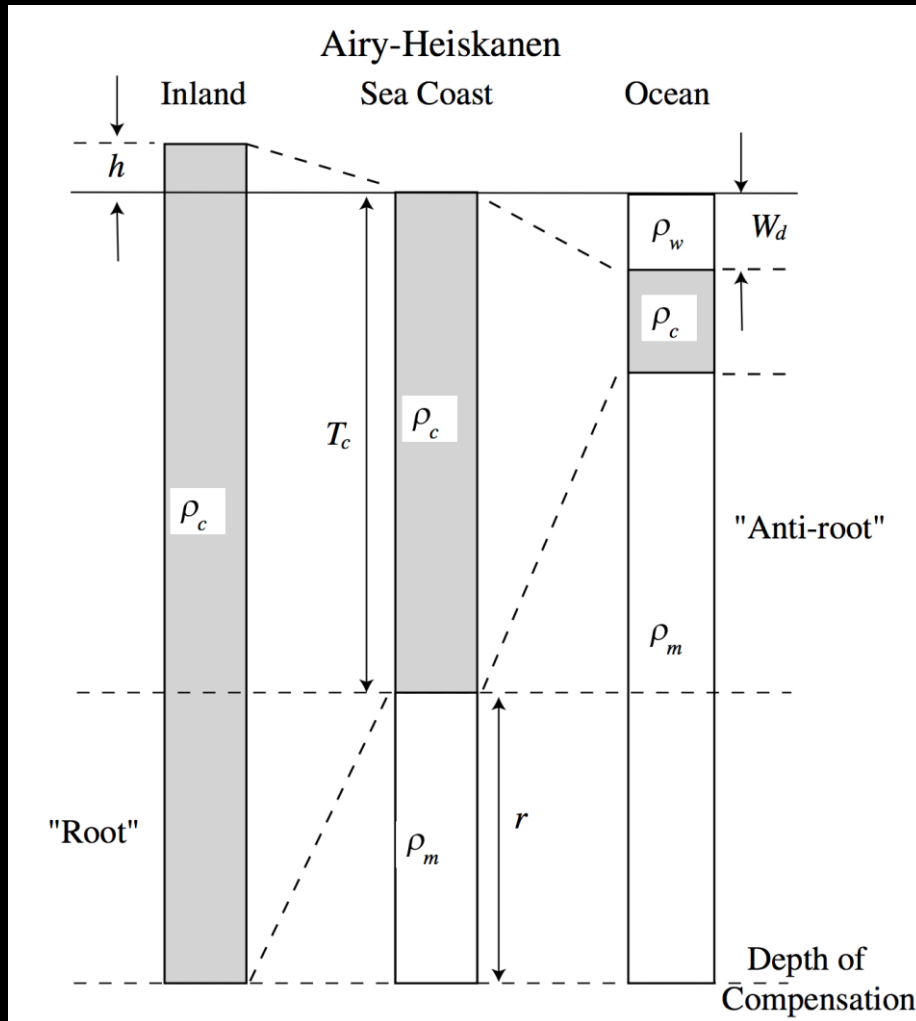


➤ **Not in** hydrostatic equilibrium

$$\rho = \rho(r), \omega$$



Isostasy



Isostatic equilibrium:

- Equal weight of crustal columns at the depth of compensation
- Deviatoric stresses within the isostatically compensated layer are minimized

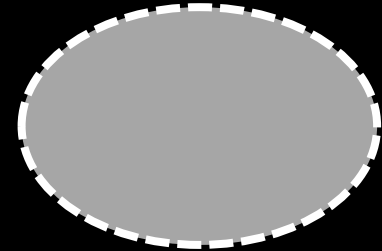
Watts, 2001

Gravity anomalies

- Free-air anomaly

$$\sigma_{\text{FA}} = \sigma_{\text{obs}} - \sigma_{\text{model}}$$

$\sigma_{\text{model}} =$ gravity of
hydrostatic figure

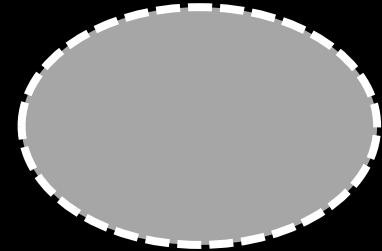


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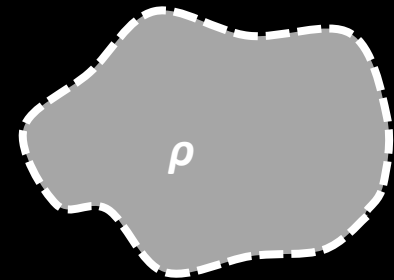
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- Bouguer anomaly

$$\sigma_{\text{BA}} = \sigma_{\text{obs}} - \sigma_{\text{model}}$$

$\sigma_{\text{model}} =$ gravity of shape
assuming ρ



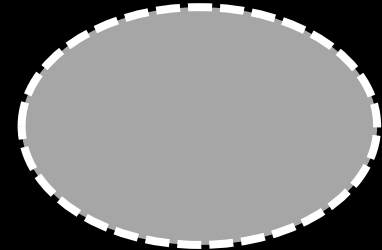
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gravity of
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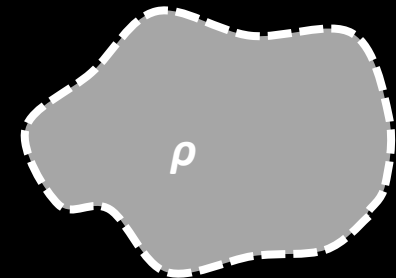


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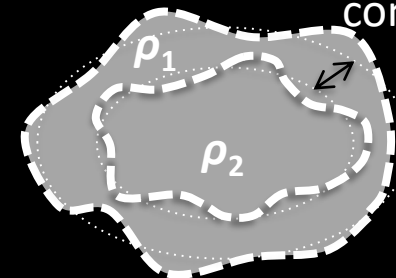
- Isostatic anomaly

$$\sigma_{\text{IA}} = \sigma_{\text{obs}} - \sigma_{\text{model}}$$

h – depth of
compensation

$$\sigma_{\text{model}} =$$

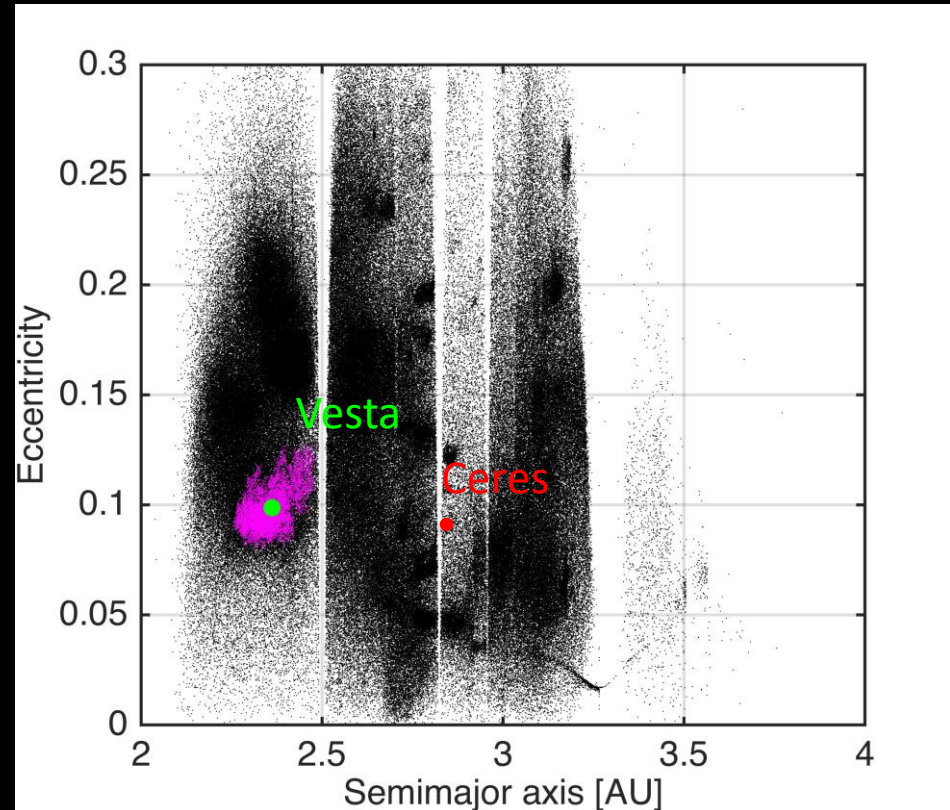
gravity assuming
isostasy for ρ_1, ρ_2, h



Why Ceres?

- **Largest body in the asteroid belt**
- **Low density implies high volatile content**
- **Conditions for subsurface ocean**
- **Much easier to reach than other ocean worlds**

Ceres location in the asteroid belt



What did we know before Dawn

- **Castillo-Rogez and McCord 2010**

Ceres accreted as a mixture of ice and rock just a few My after the condensation of Calcium Aluminum-rich Inclusions (CAIs), and later differentiated into a water mantle and a mostly anhydrous silicate core.

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- **Zolotov 2009**

Ceres formed relatively late from planetesimals consisting of hydrated silicates.

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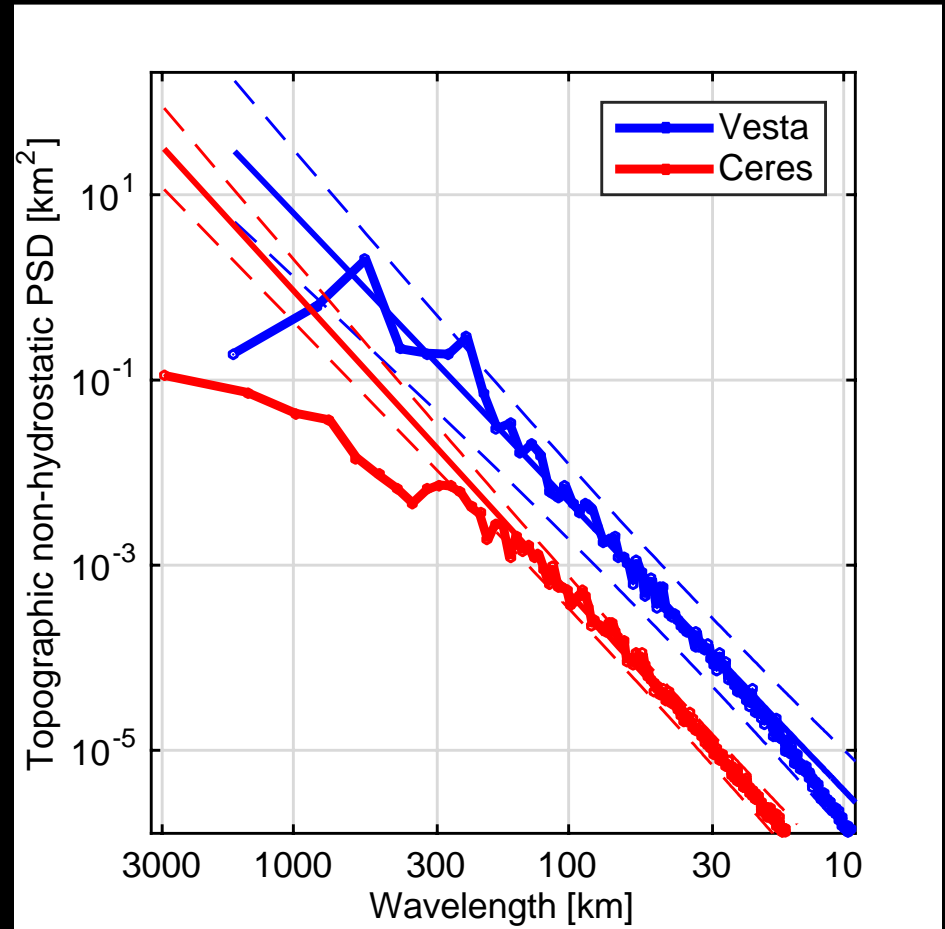
Ceres formed relatively late from planetesimals consisting of hydrated silicates.

- **Bland 2013**

If Ceres *does* contain a water ice layer, its warm diurnally-averaged surface temperature ensures extensive viscous relaxation of even small impact craters especially near equator

Evidence for viscous relaxation

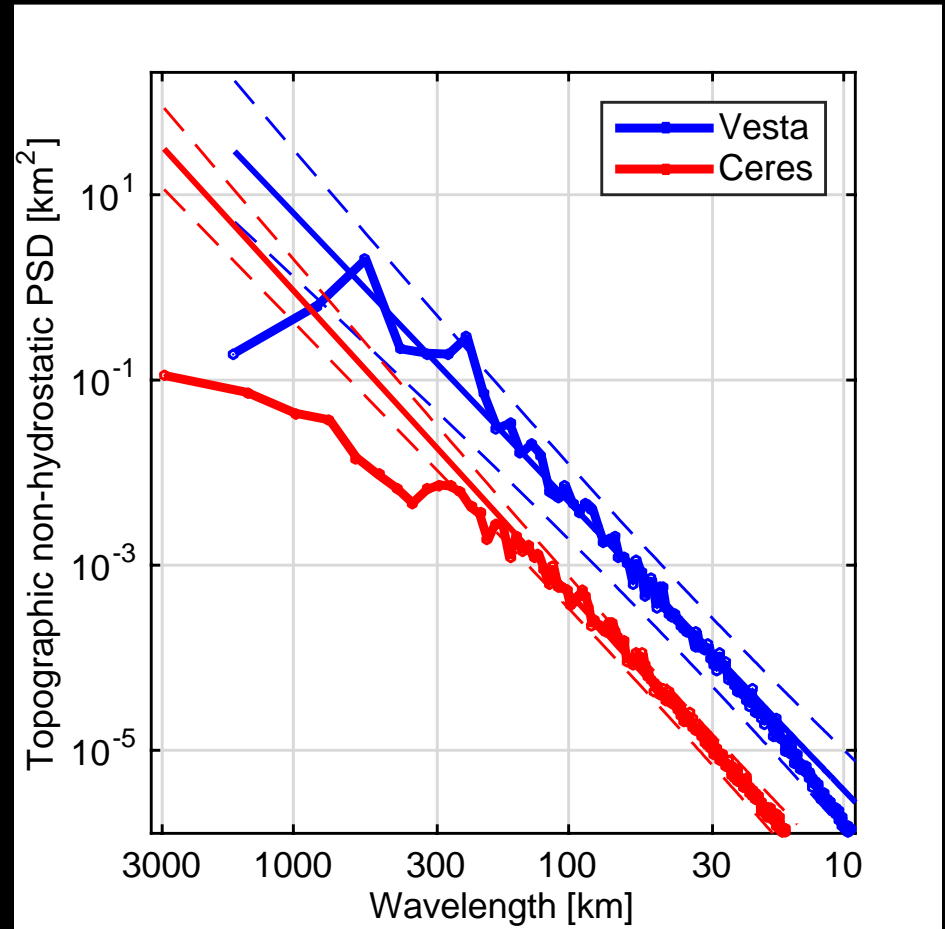
- More general approach: study topography power spectrum



Ermakov et al., in prep for JGR

Evidence for viscous relaxation

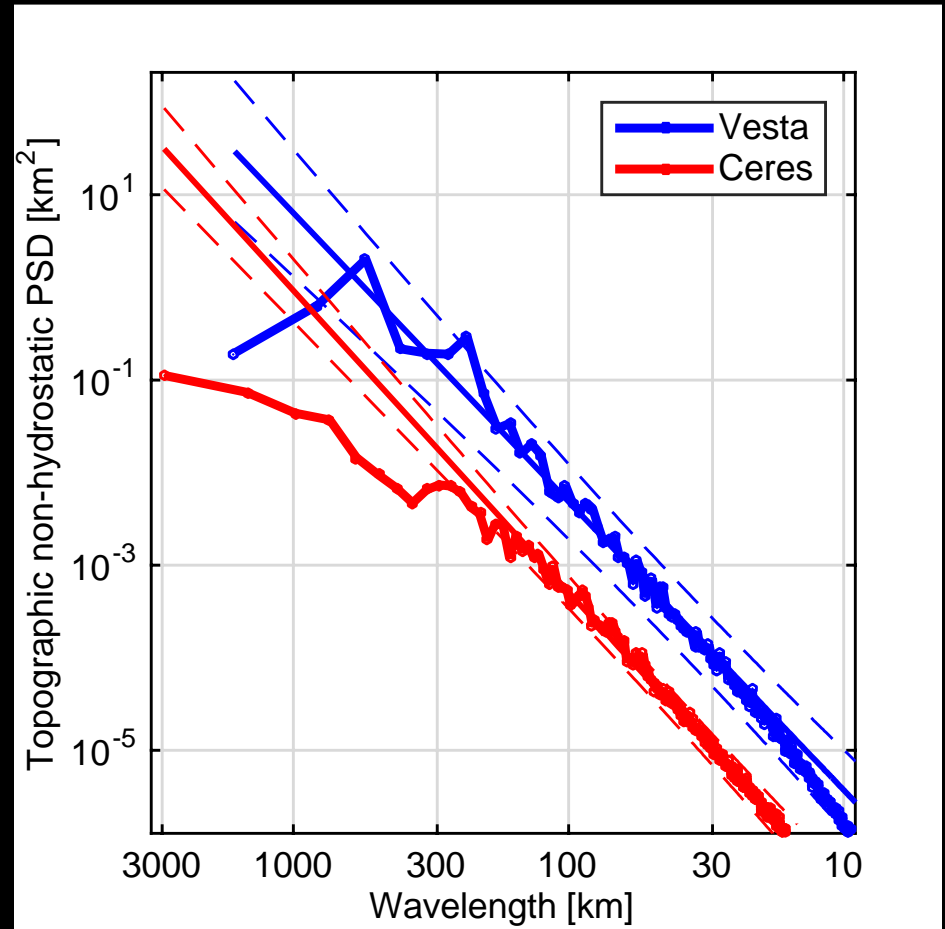
- **More general approach: study topography power spectrum**
- **Power spectra for Vesta closely fits with the power law to the lowest degrees ($\lambda < 750$ km)**



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Evidence for viscous relaxation

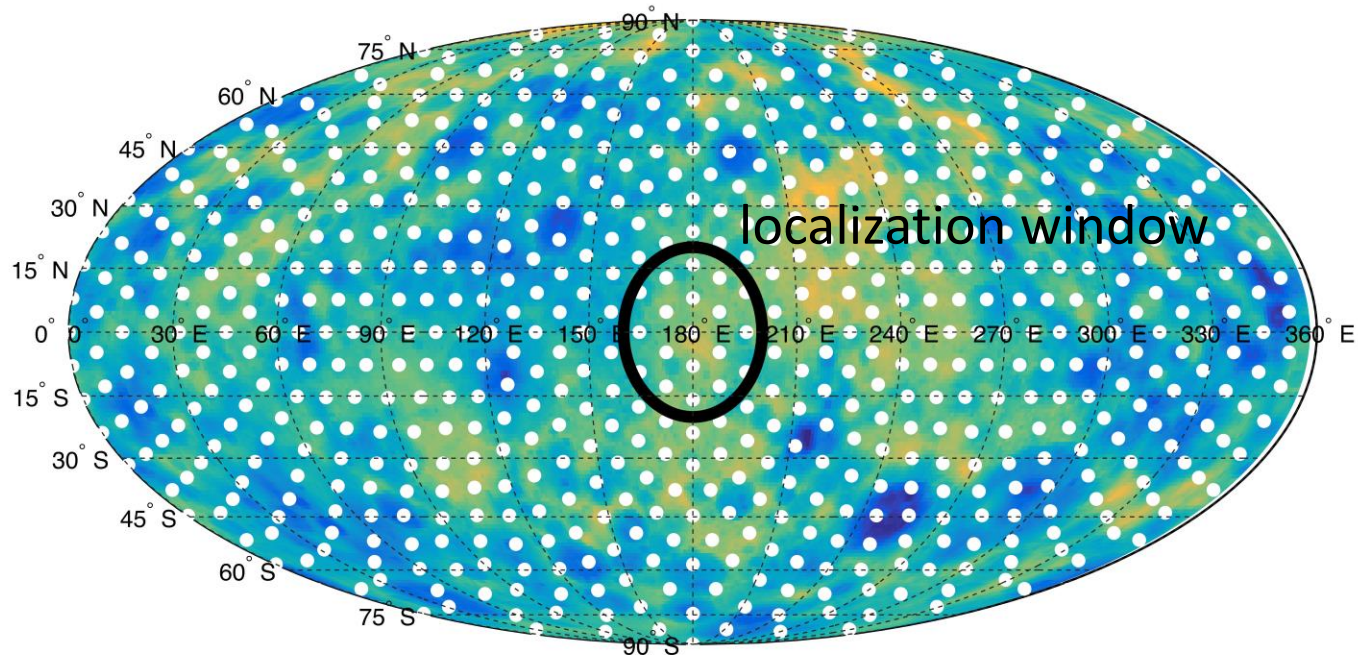
- **More general approach: study topography power spectrum**
- **Power spectra for Vesta closely fits with the power law to the lowest degrees ($\lambda < 750$ km)**
- **Ceres power spectrum deviates from the power law at $\lambda > 270$ km**



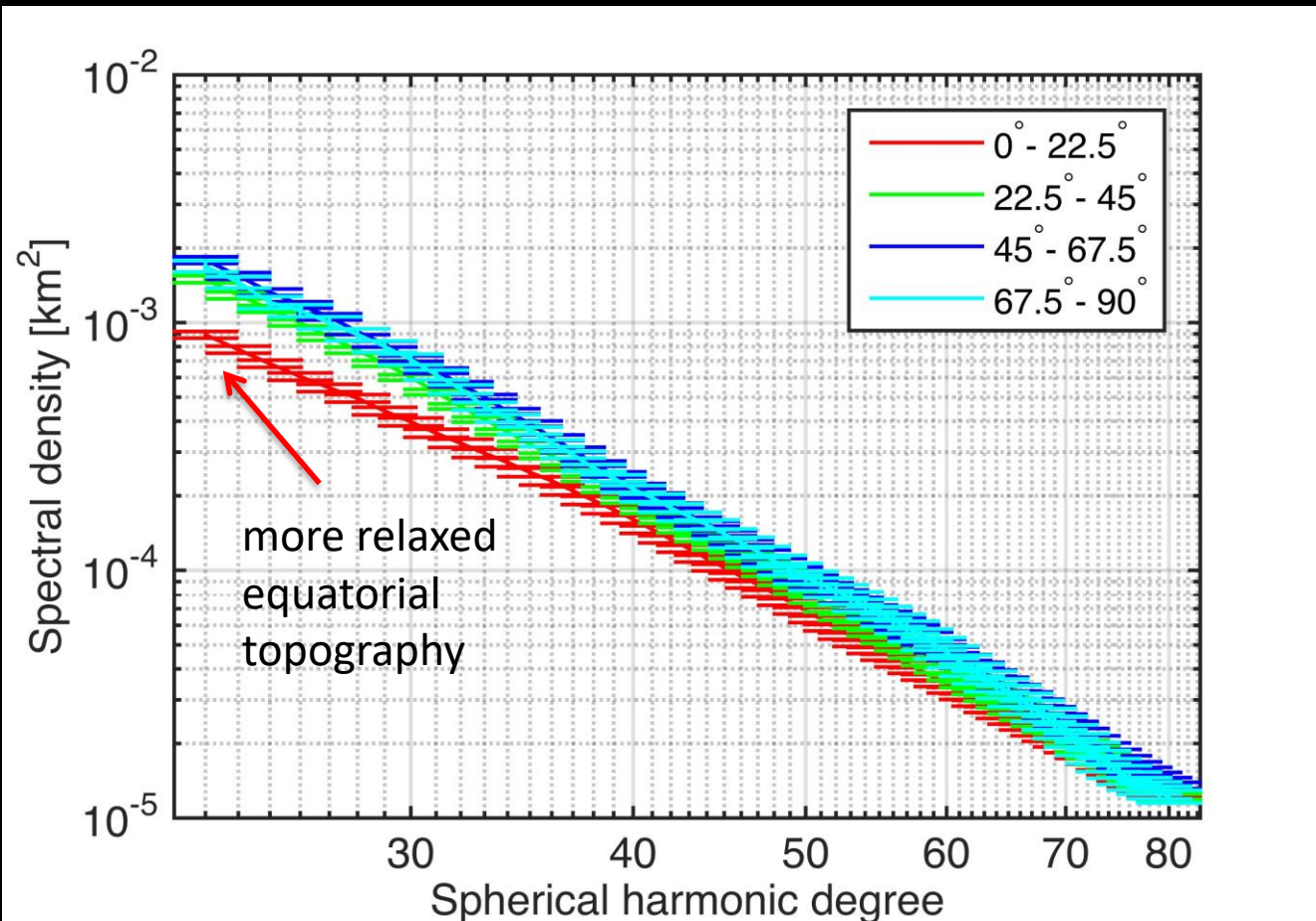
Ermakov et al., in prep for JGR

Spectral-spatial localization of topography

- Use Slepian windows to minimize spectral and spatial leakage
- Icosahedron tessellation for uniform distribution of windows



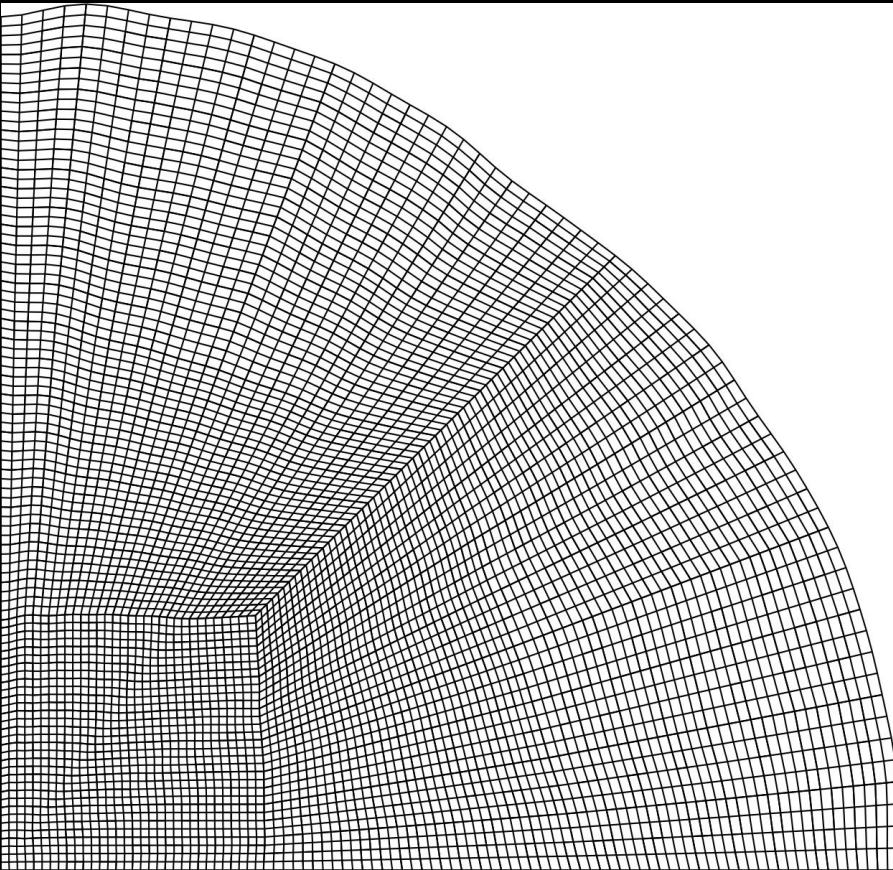
Latitude dependence of relaxation



Ermakov et al., in prep for JGR

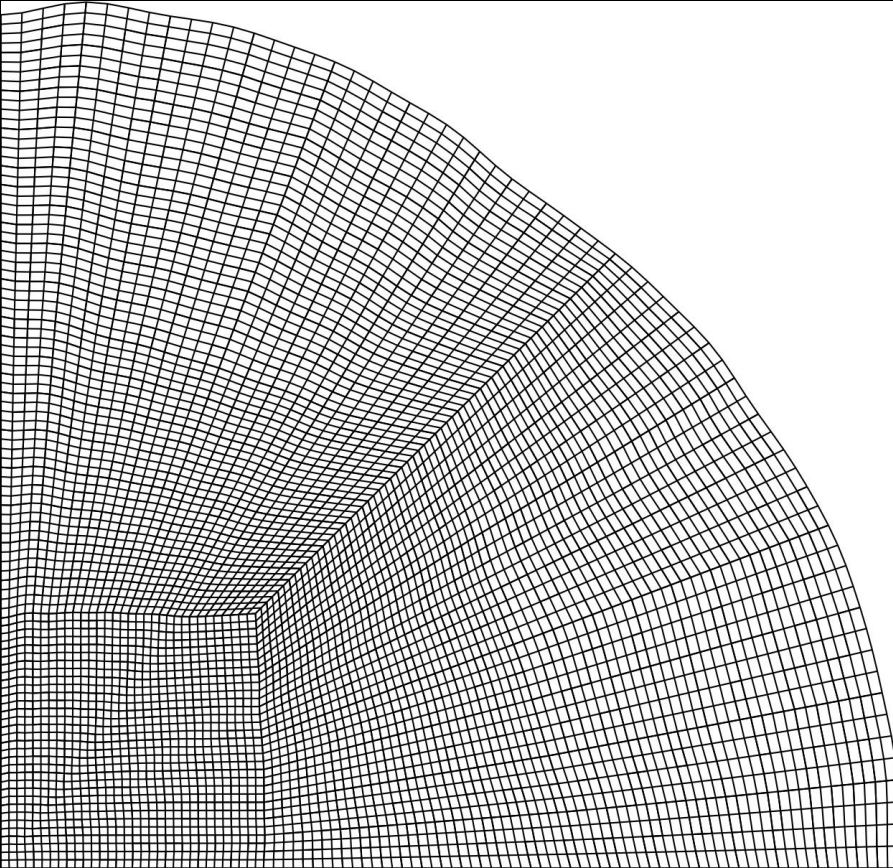
Finite element model

- Assume a density and rheology structure



Fu et al., 2014; Fu et al., 2017 in prep for EPSL

Finite element model



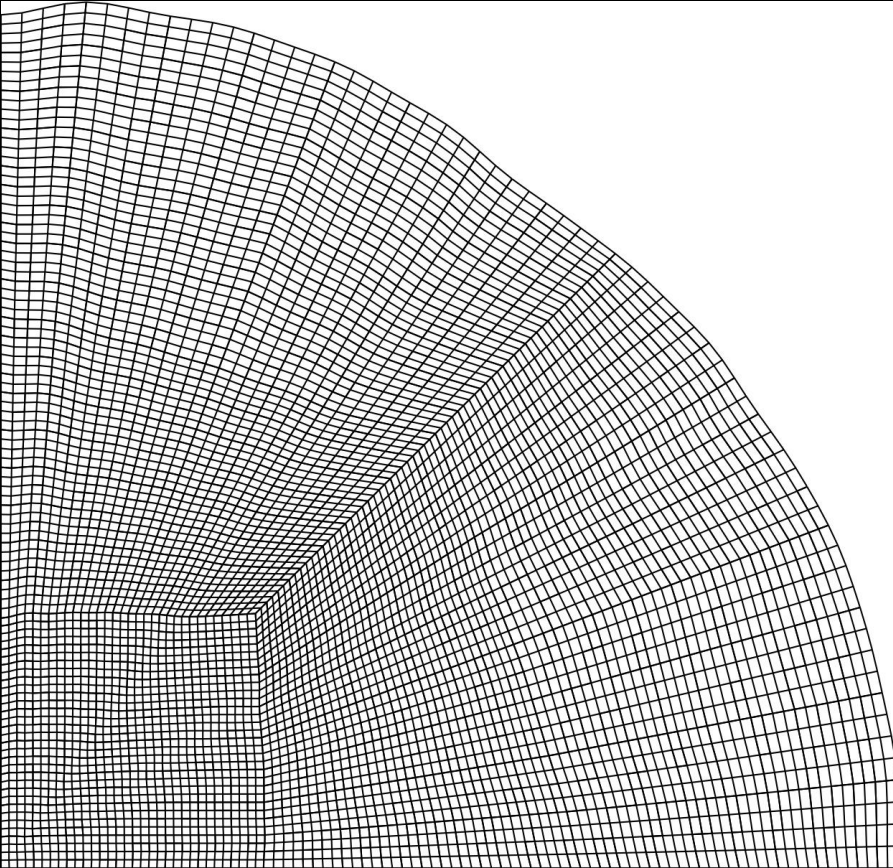
- Assume a density and rheology structure
- Solve Stokes equation for an incompressible flow using deal.ii library

$$\partial_i (2\eta \dot{\epsilon}_{ij}) - \partial_i p = -g_i \rho$$

$$\nabla_i u_i = 0$$

Fu et al., 2014; Fu et al., 2017 in prep for EPSL

Finite element model



Fu et al., 2014; Fu et al., 2017 in prep for EPSL

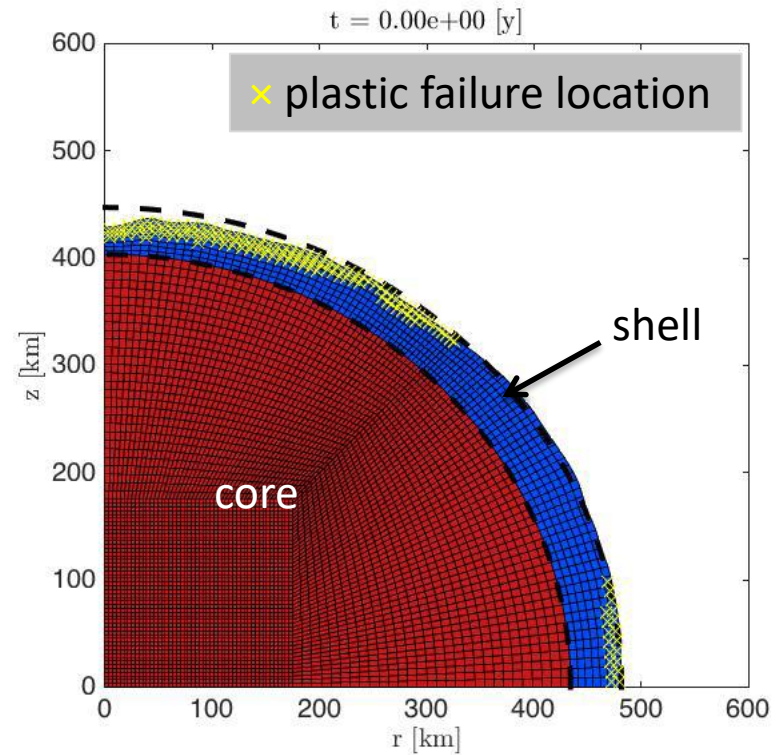
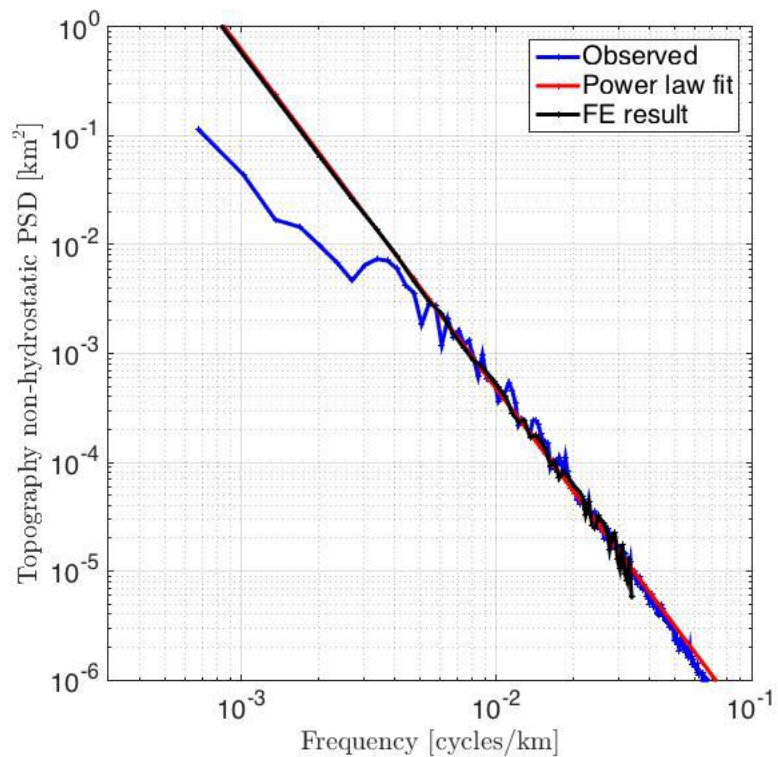
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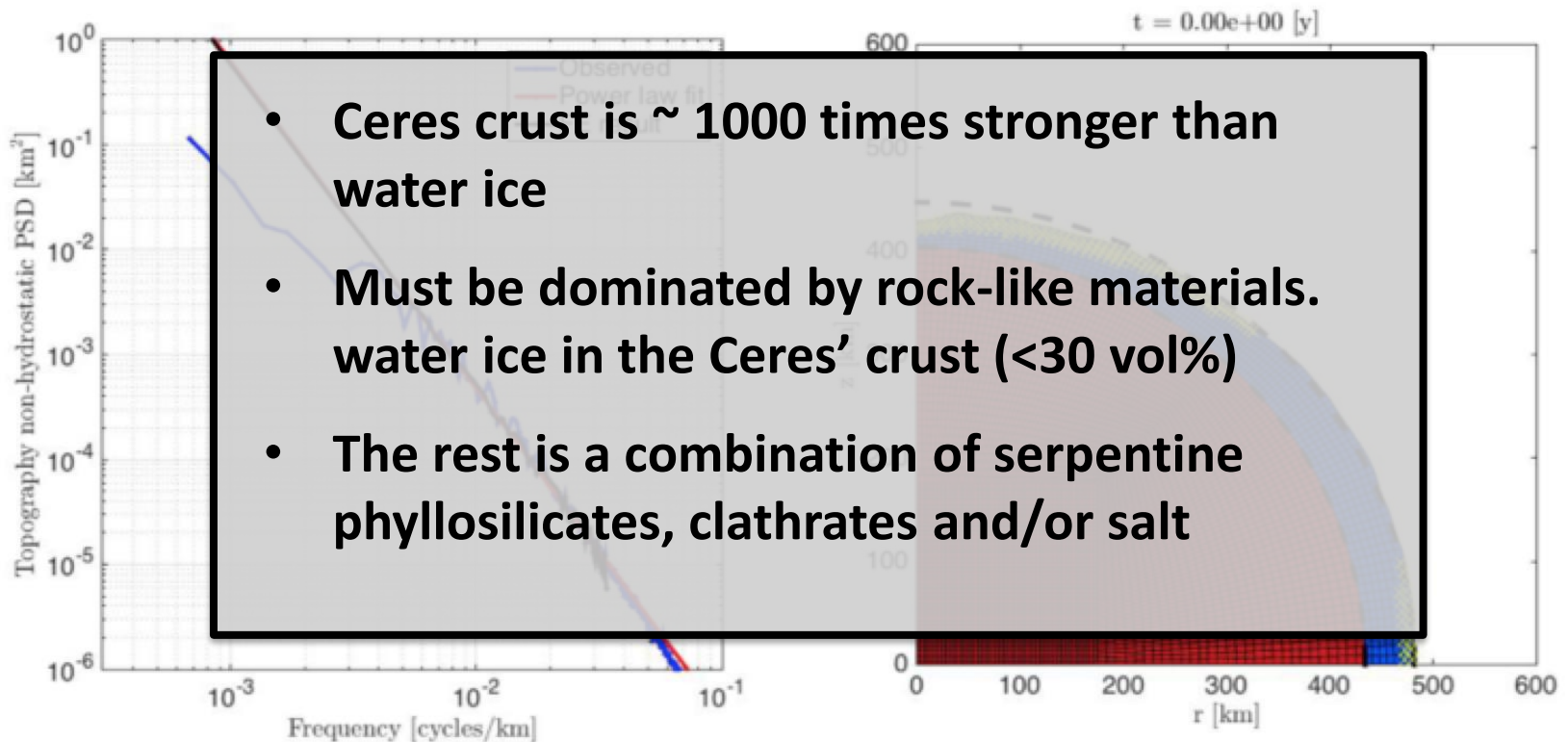
$$\nabla_i u_i = 0$$

- Compute the evolution of the outer surface power spectrum

Example of a FE modeling run

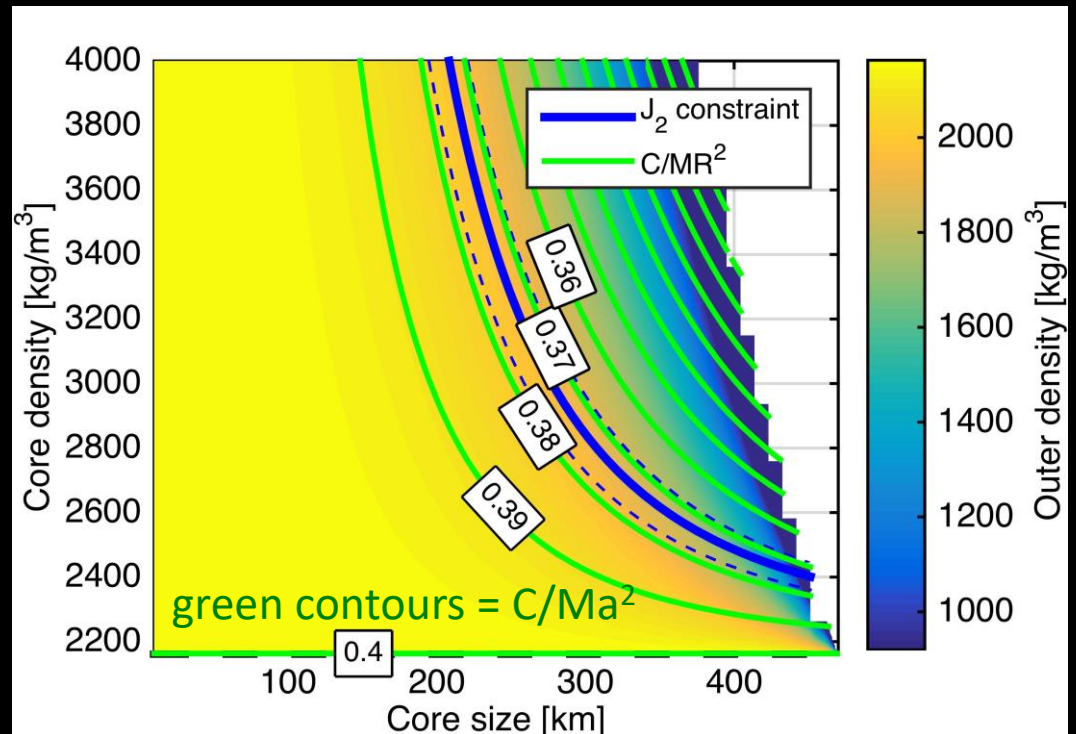


Finite element modeling results



Two-layer model

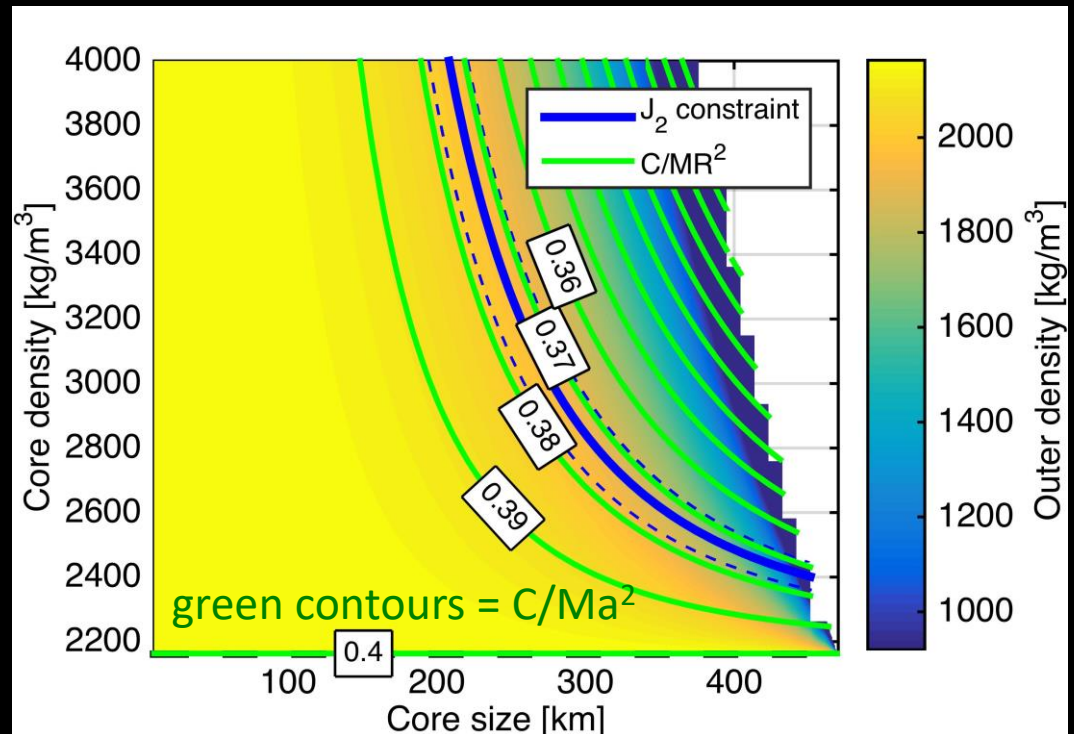
- Simplest model to interpret the gravity-topography data



Using Tricarico 2014 for computing hydrostatic equilibrium

Two-layer model

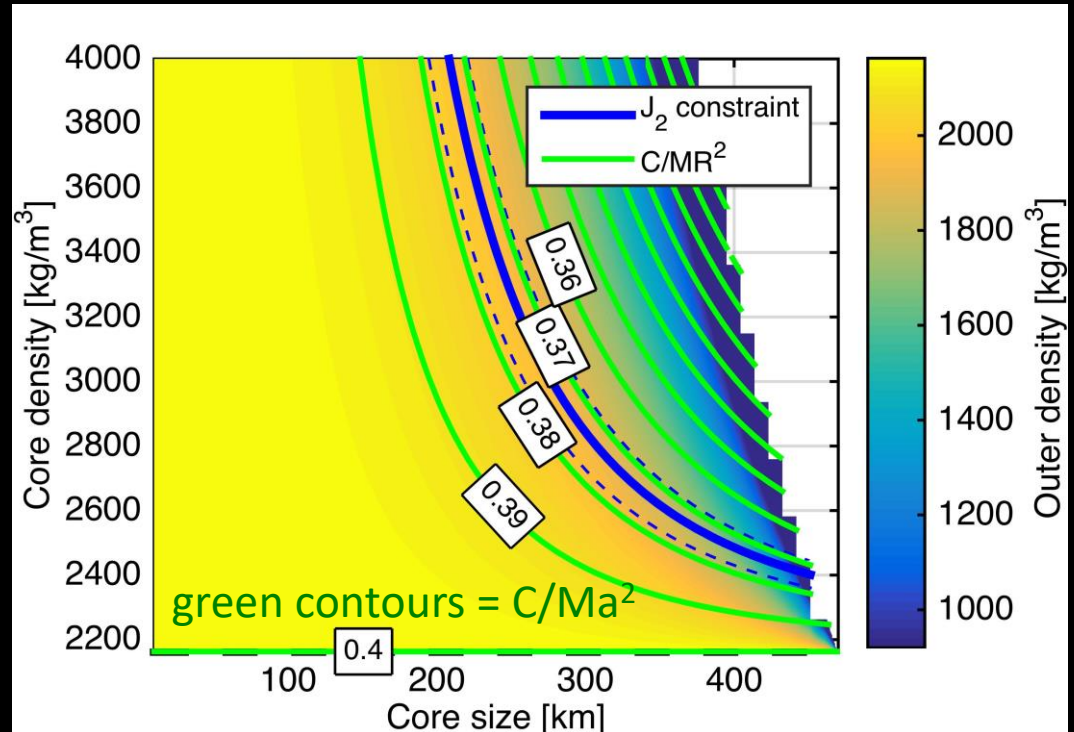
- Simplest model to interpret the gravity-topography data
- Only 5 parameters: two densities, two radii and rotation rate



Using Tricarico 2014 for computing hydrostatic equilibrium

Two-layer model

- Simplest model to interpret the gravity-topography data
- Only 5 parameters: two densities, two radii and rotation rate
- Yields $C/Ma^2 = 0.373$
 $C/M(R_{vol})^2 = 0.392$



Using Tricarico 2014 for computing hydrostatic equilibrium

Isostatic model

Z_n - gravity-topography admittance

$$Z_n = \frac{S_{gt}}{S_{tt}}$$

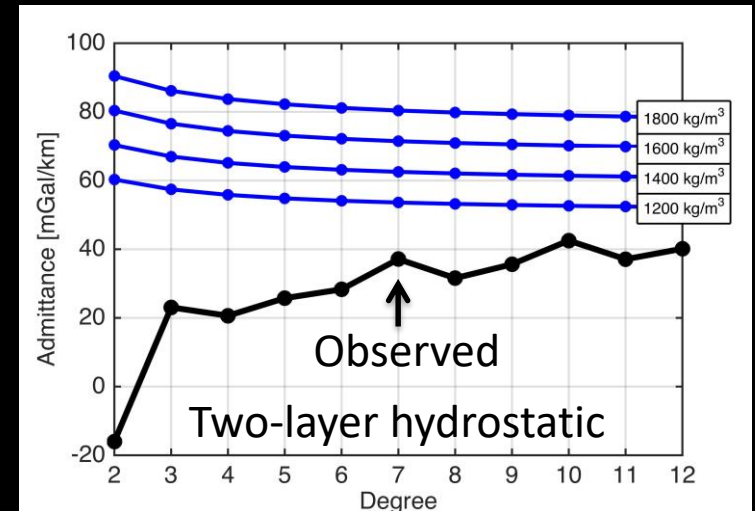
Isostatic model

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$$Z_n = \frac{S_{gt}}{S_{tt}}$$

➤ Linear two-layer hydrostatic model

$$Z_n = \frac{GM}{R^3} \frac{3(n+1)}{2n+1} \frac{r_{crust}}{r_{mean}}$$



Isostatic model

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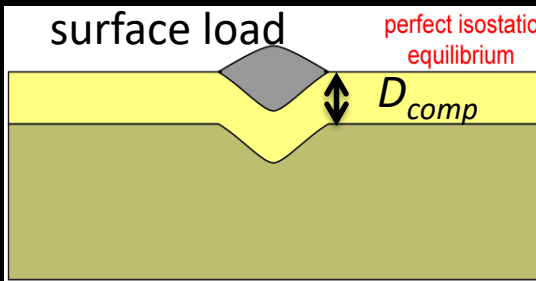
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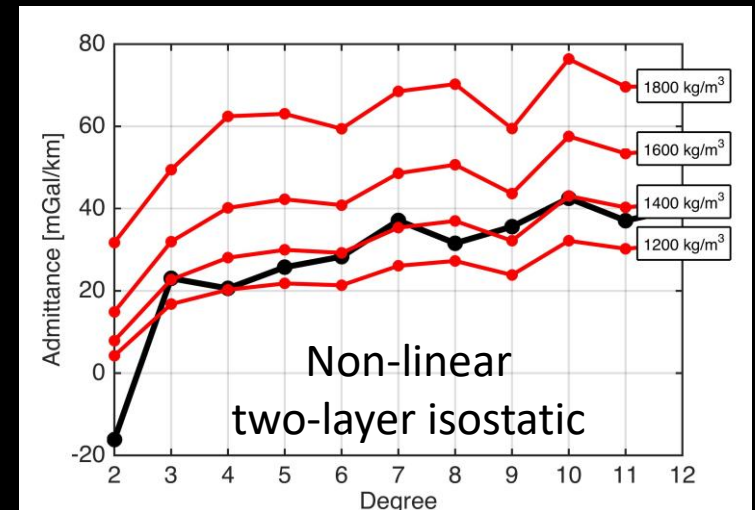
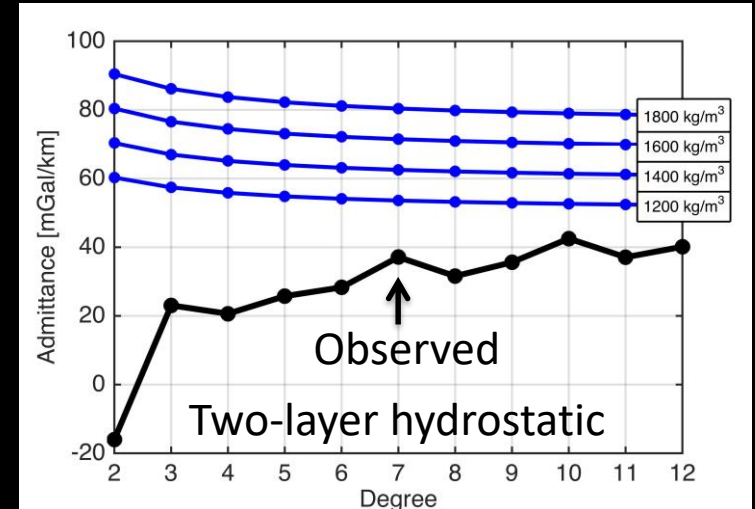
$$Z_n = \frac{GM}{R^3} \frac{3(n+1)}{2n+1} \frac{r_{crust}}{r_{mean}}$$

➤ Linear isostatic model

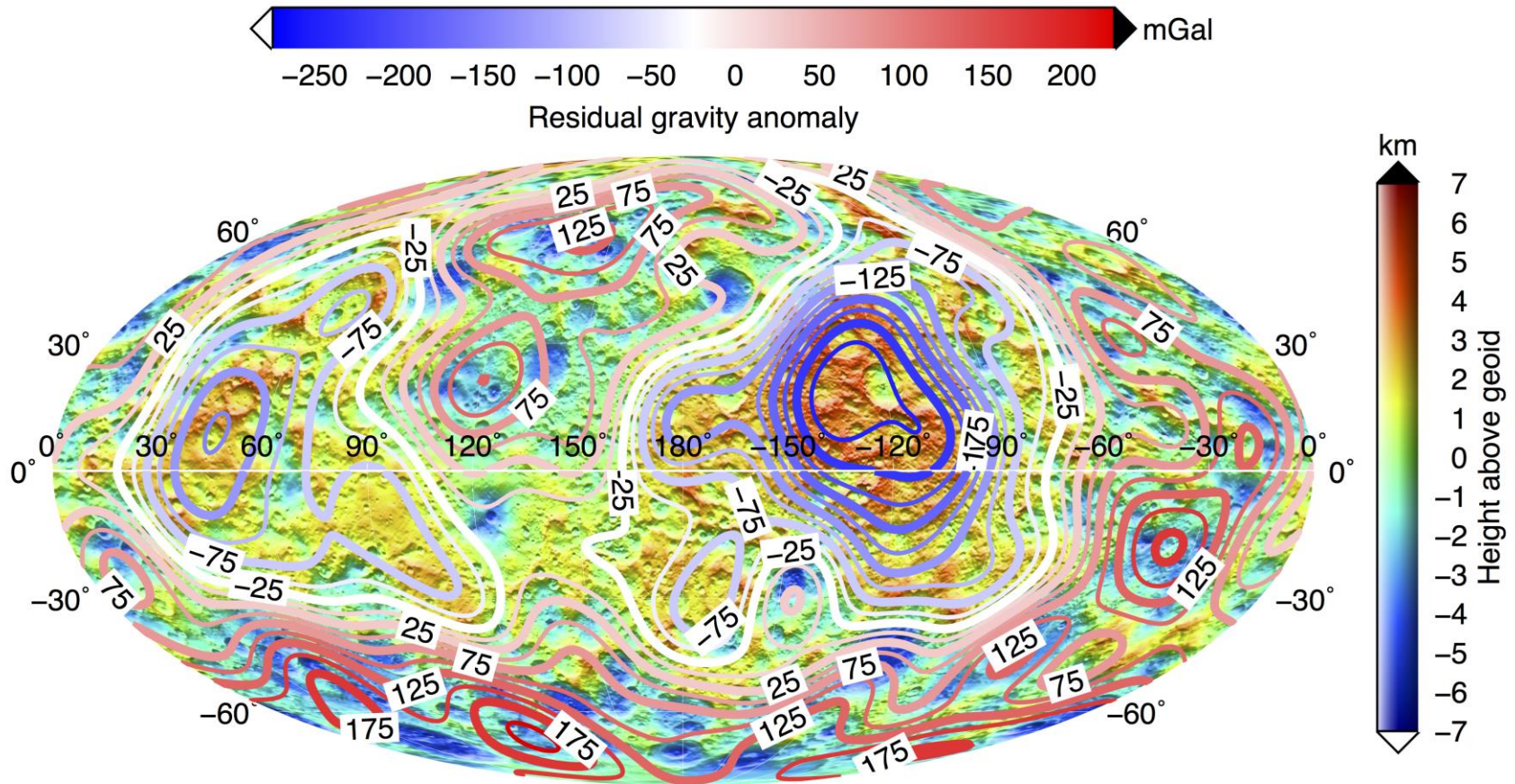
$$Z_n = \frac{GM}{R^3} \frac{3(n+1)}{2n+1} \frac{r_{crust}}{r_{mean}} \left(1 - \frac{D_{comp}}{R} \right)$$



D_{comp} - depth of compensation



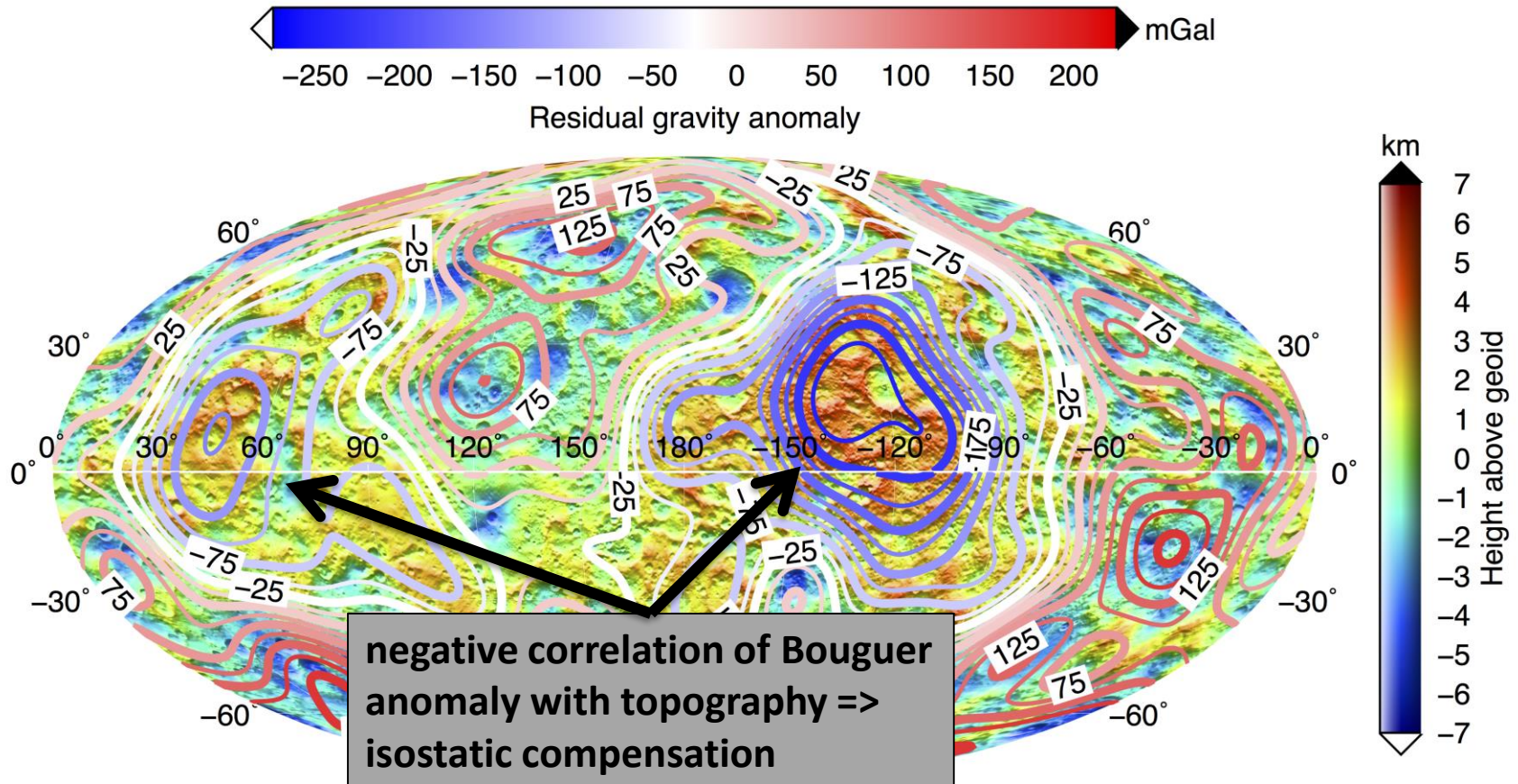
Bouguer anomaly



up to $n = 11$

Ermakov et al., in prep for JGR

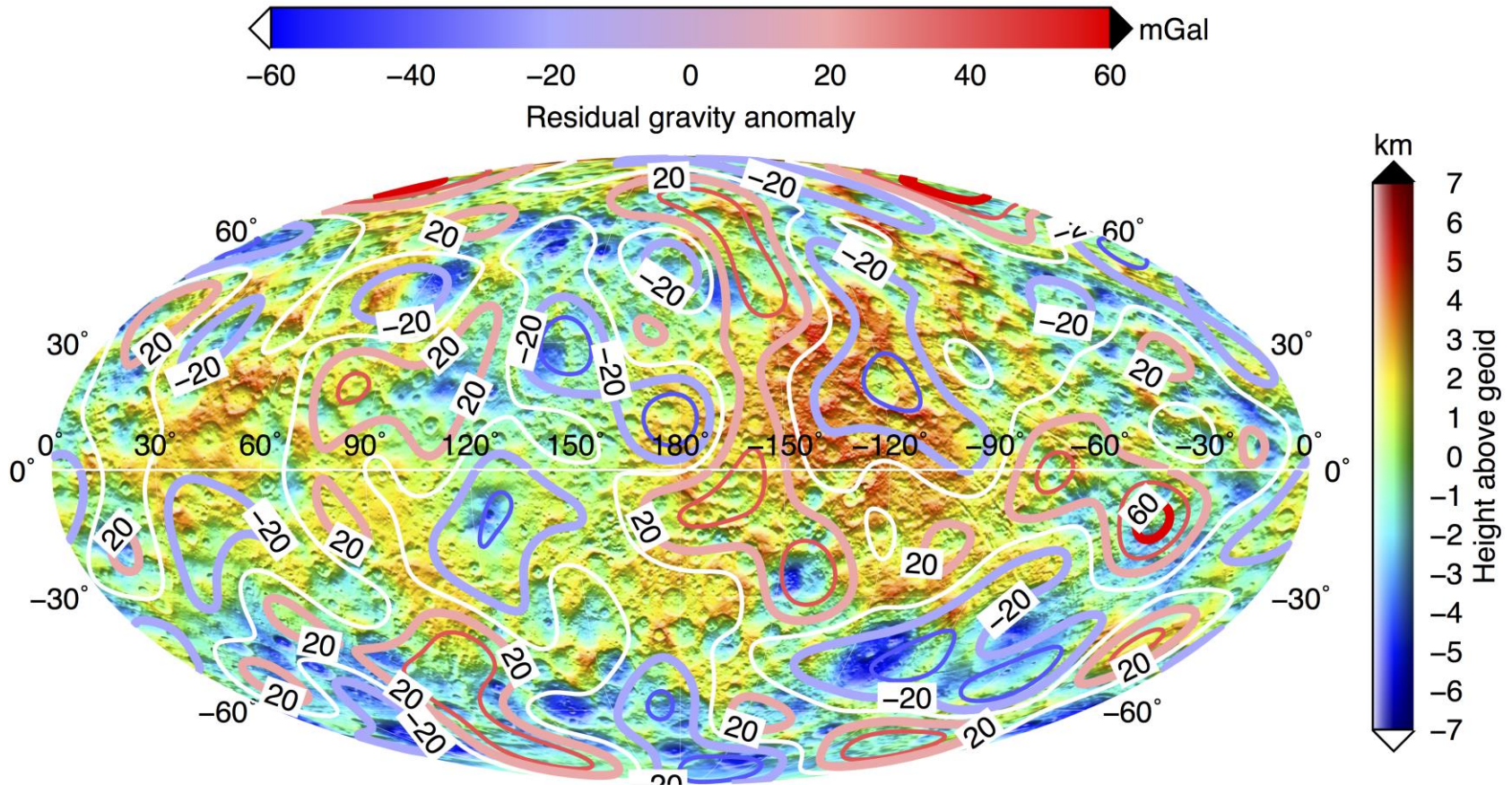
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Occator crater

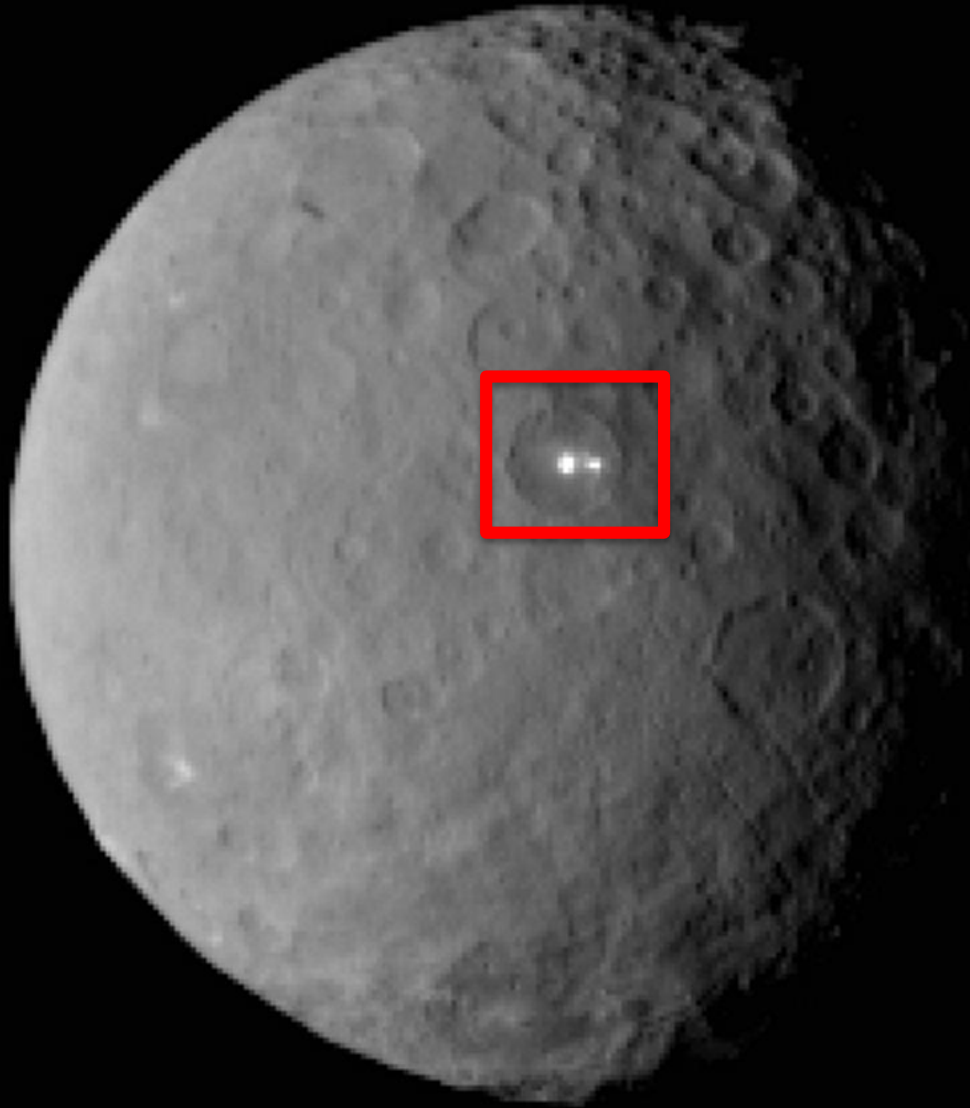


Image credit: NASA, DLR

Occator crater

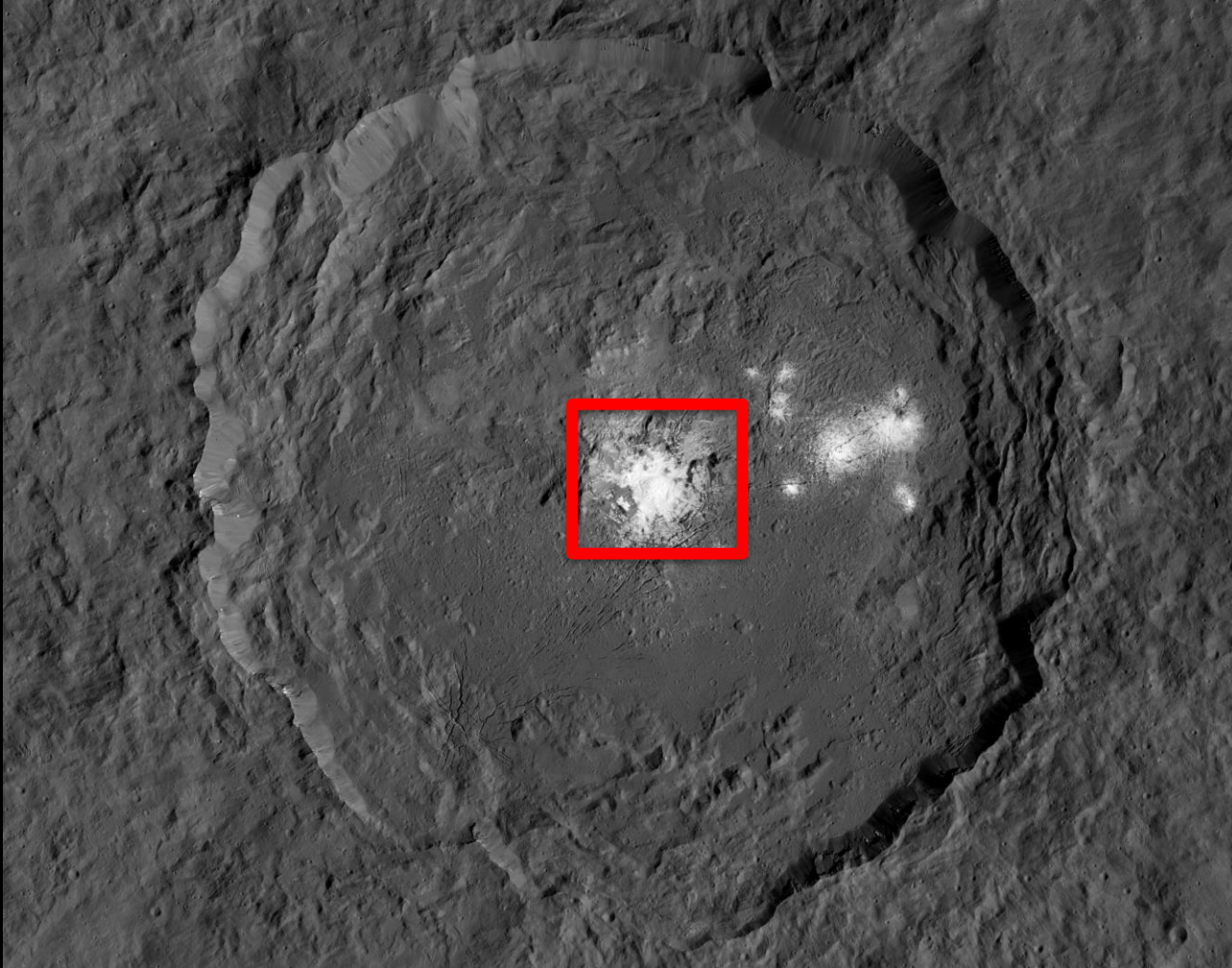


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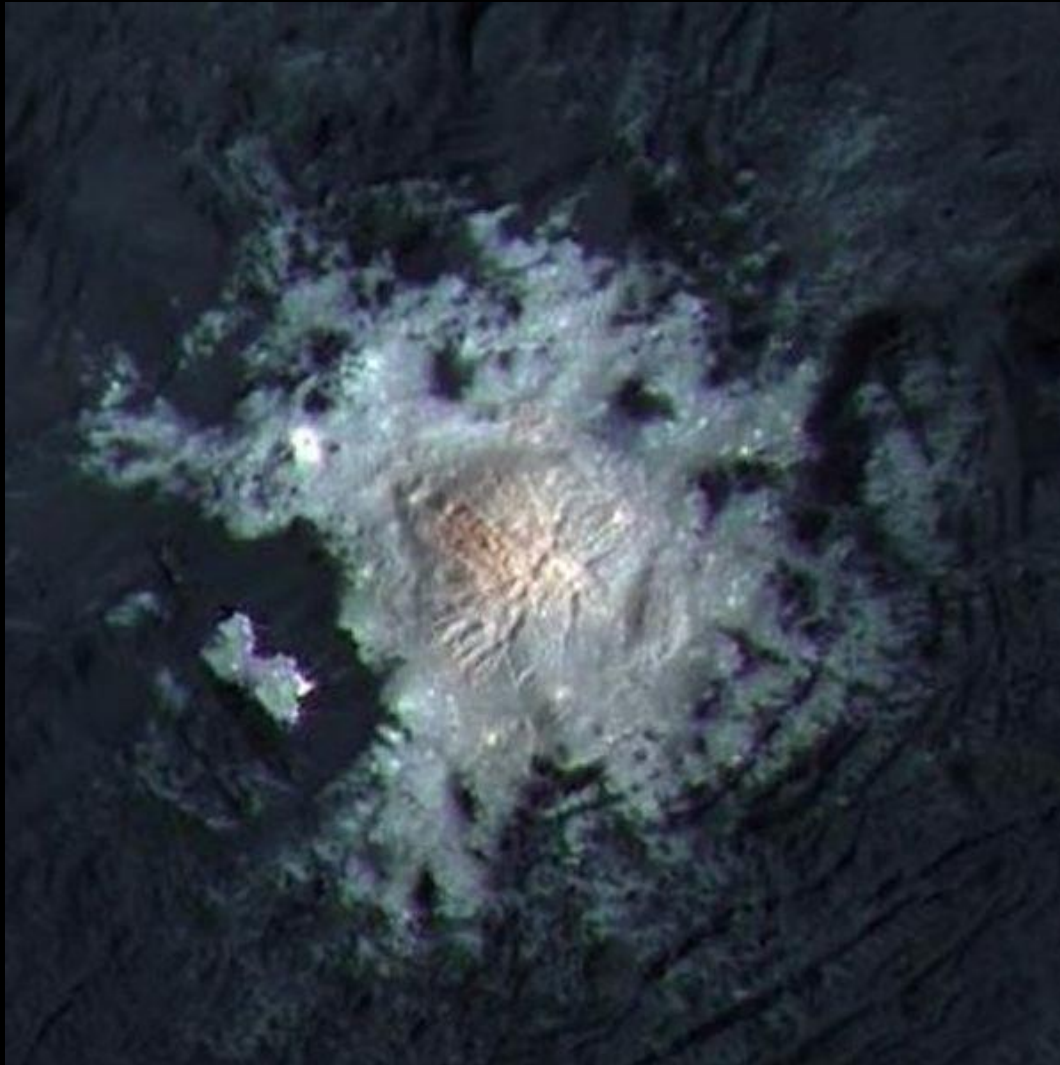
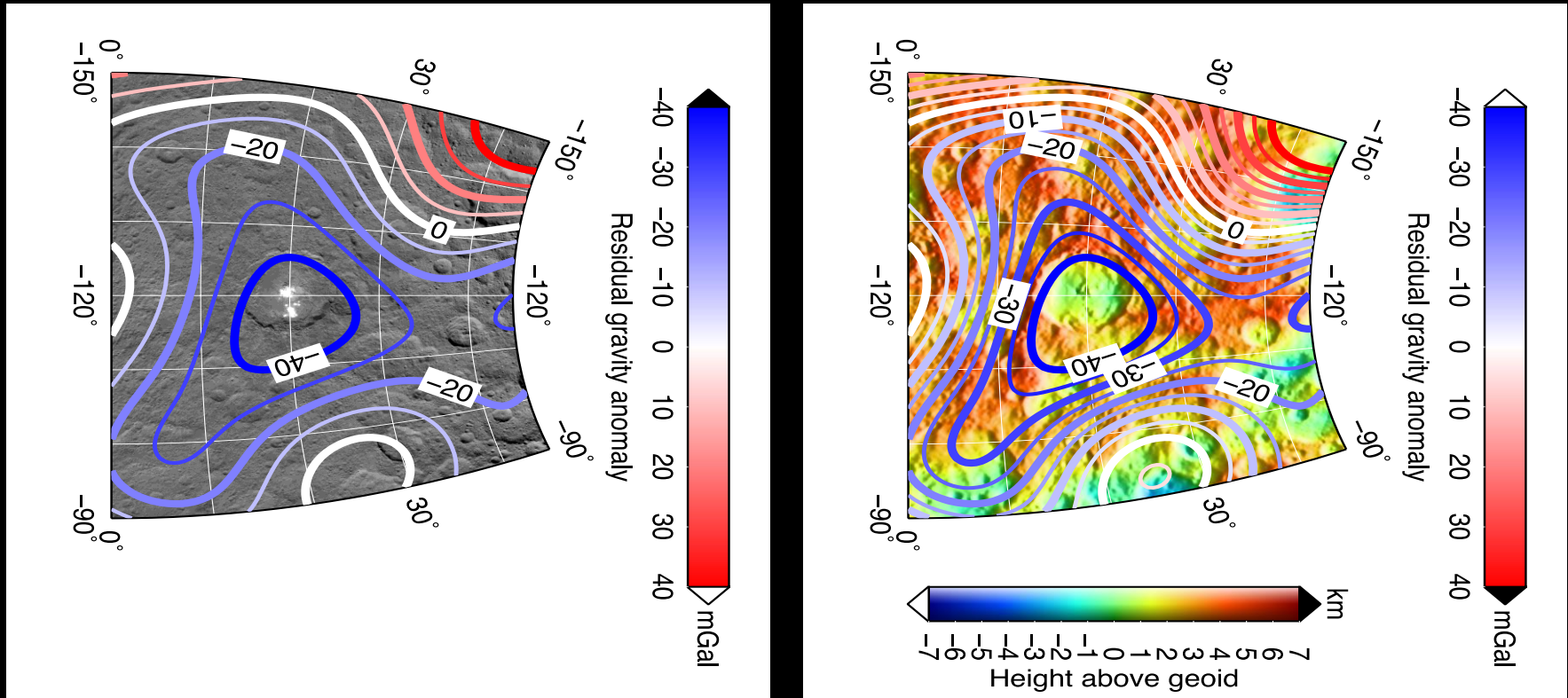


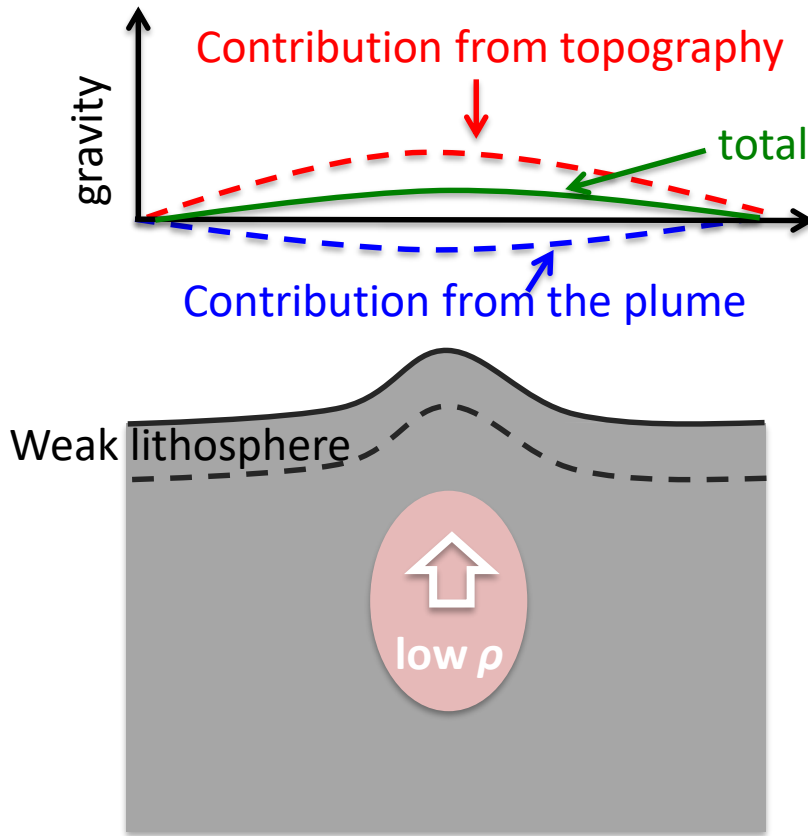
Image credit: NASA, DLR

Occator isostatic anomaly ($n > 2$)

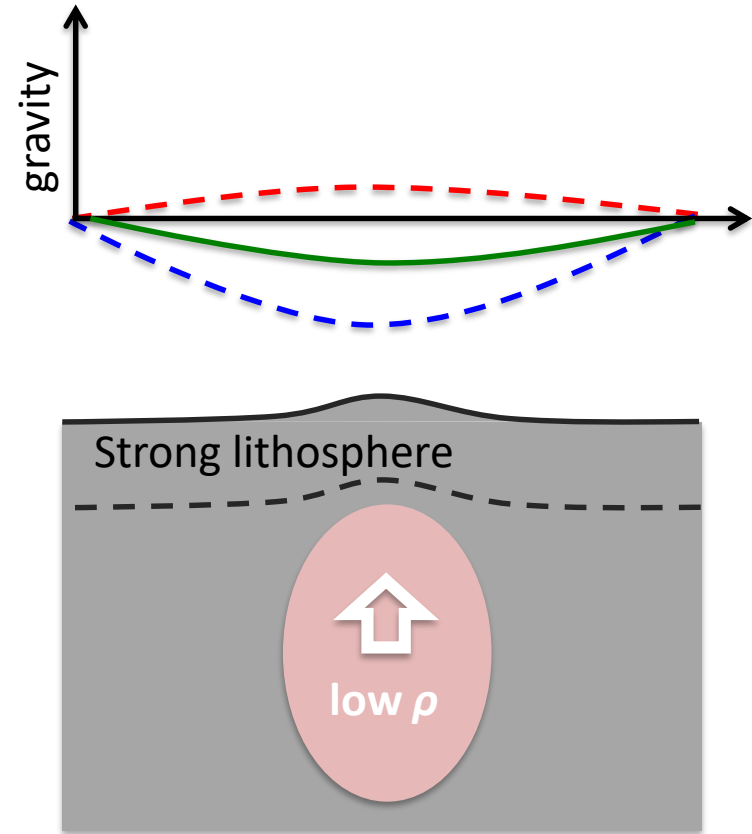


- Occator provides a linkage between internal structure and surface observations

Internal activity?

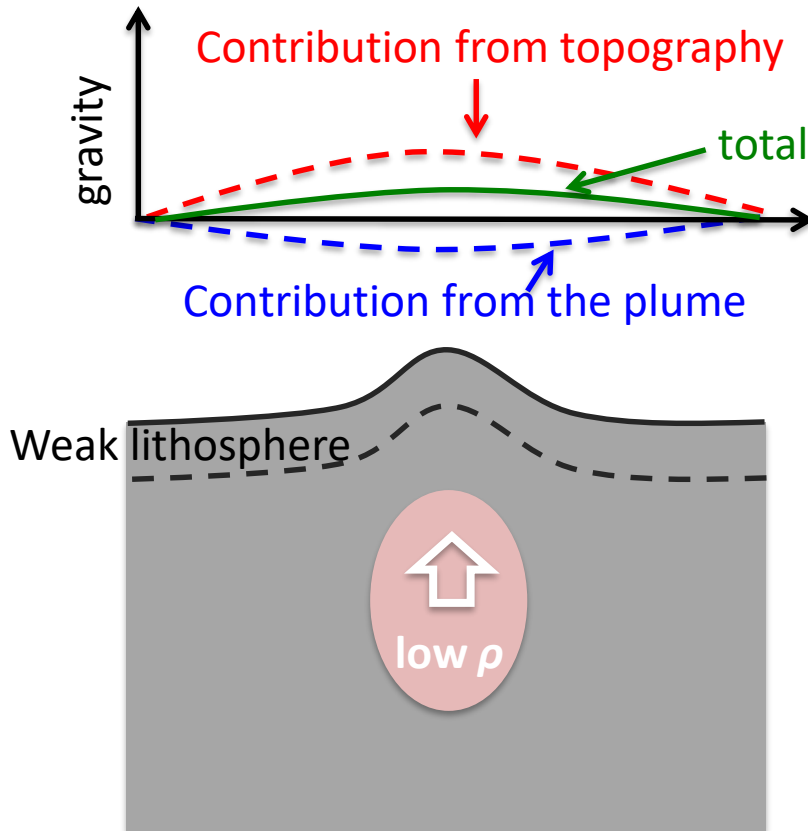


Positive gravity-topography correlation

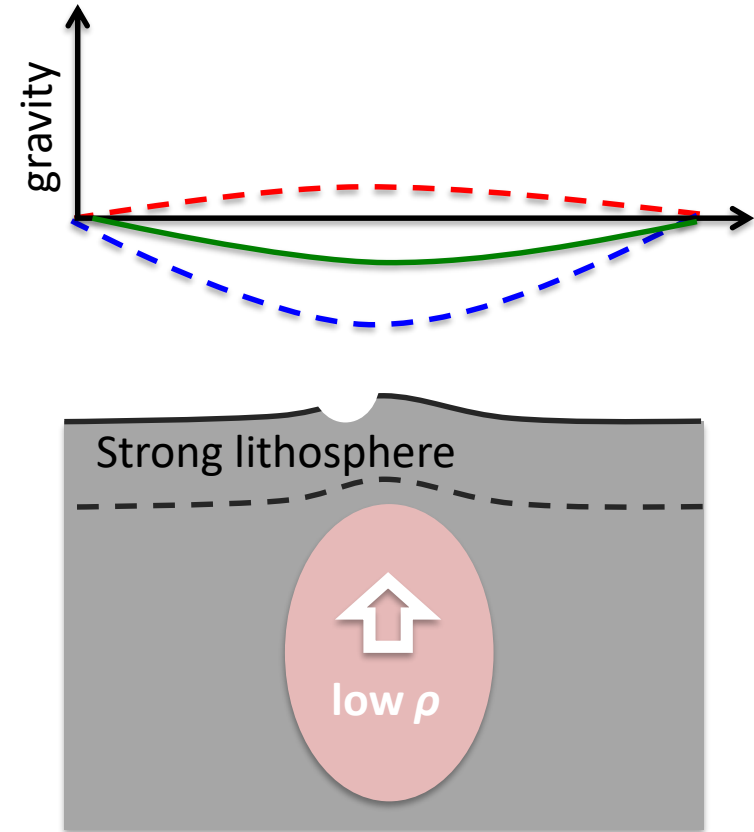


Negative gravity-topography correlation

Internal activity?

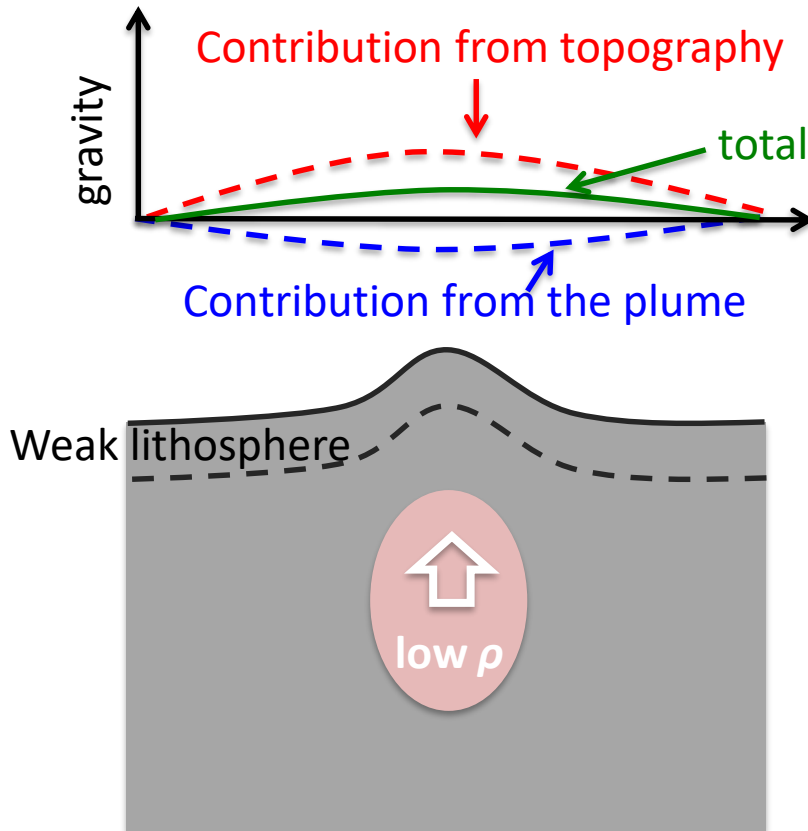


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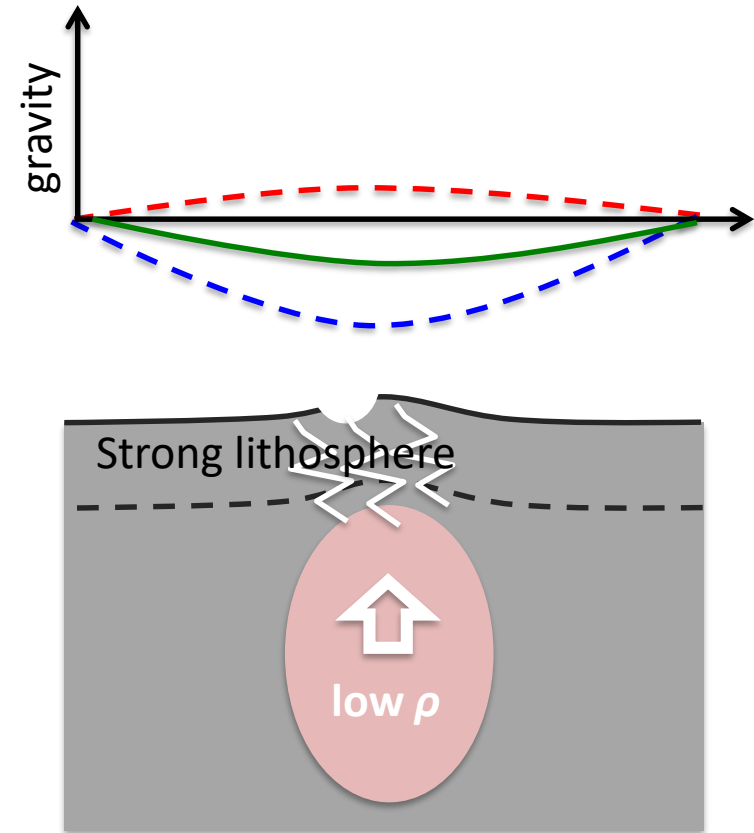


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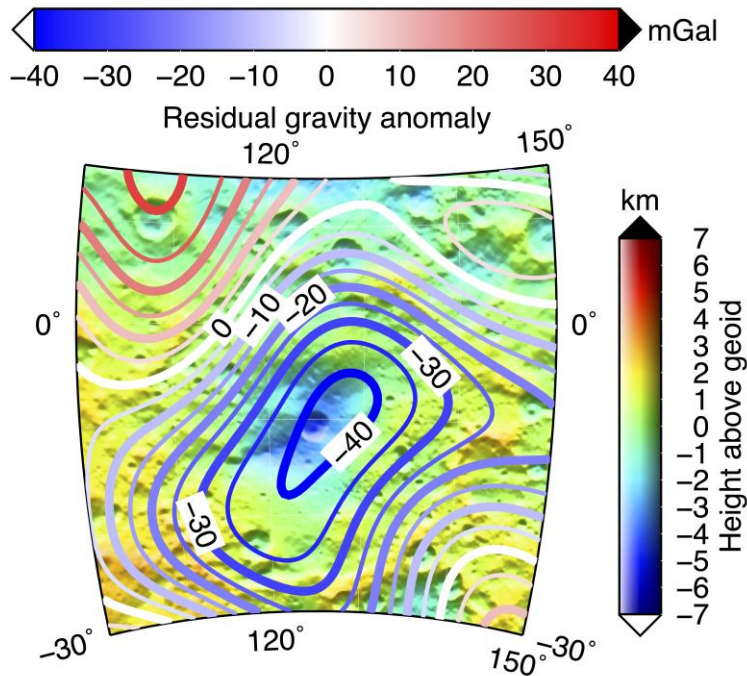
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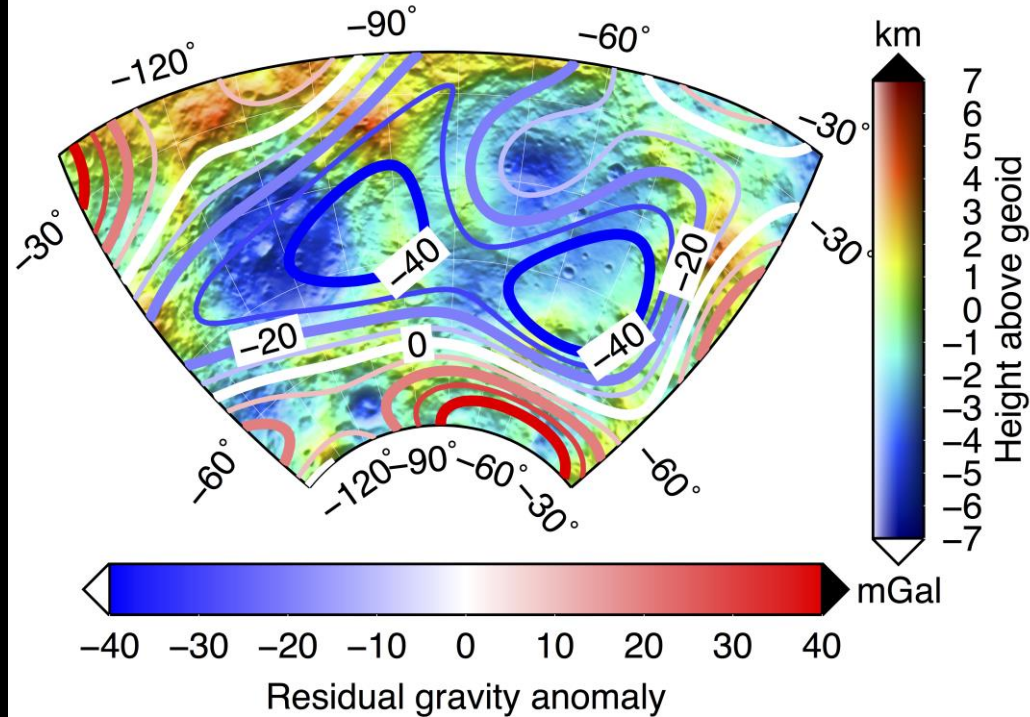
Negative gravity-topography correlation

Big basins

Kerwan



Urvara and Yalode



- Big basins are subcompensated
 - Localized volatile enrichment
 - Increased impact induced porosity

Ahuna Mons

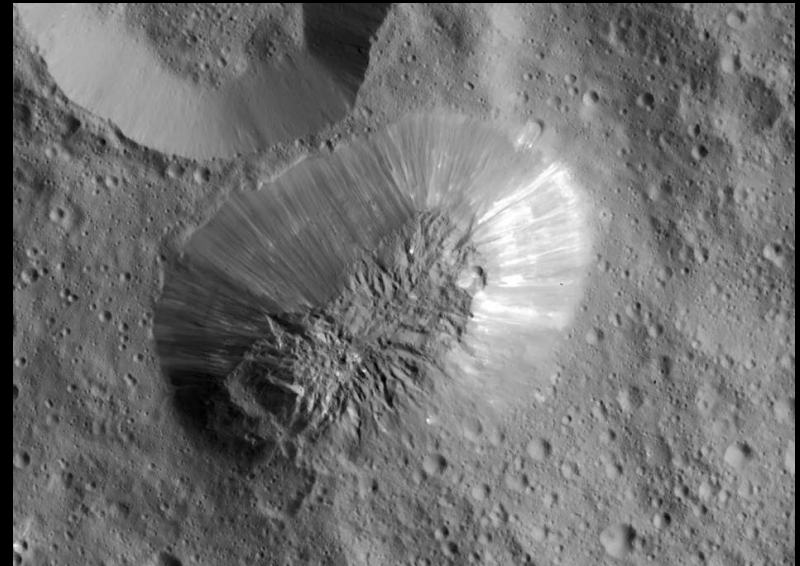
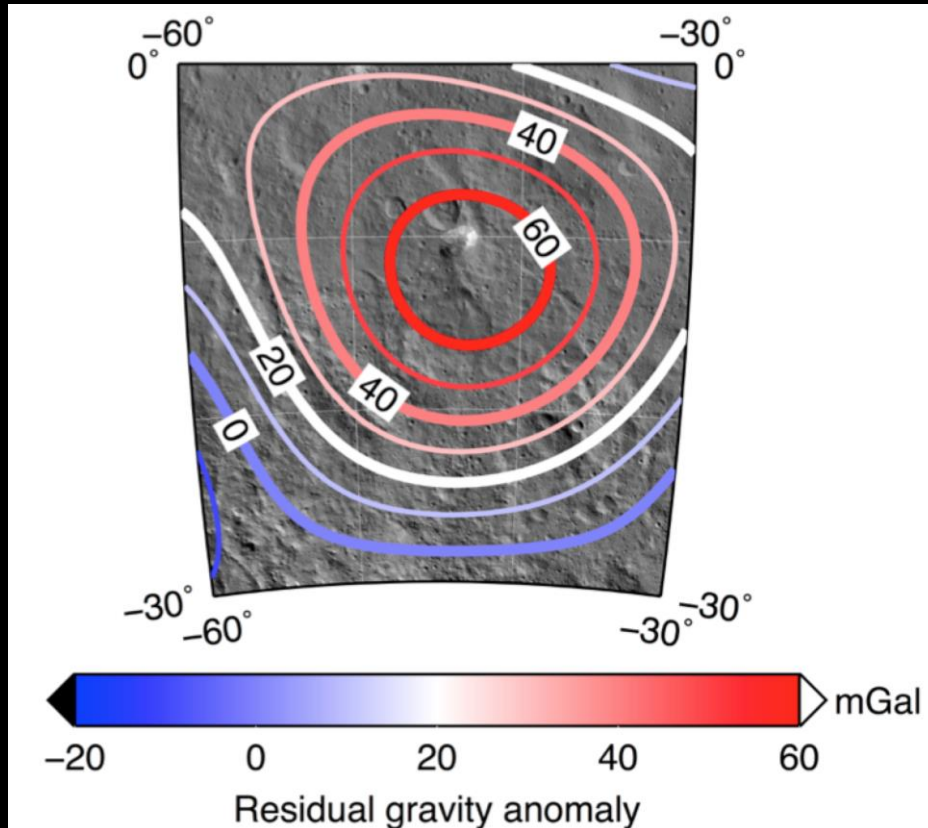


Image credit: DLR

- Ahuna Mons is proposed to be a region of cryovolcanic activity
- Having a strong isostatic (and Bouguer) anomalies, the nature of Ahuna Mons activity should be different from Occator

Summary

- Weakly differentiated based on gravity/topography data
- Temperature (not compositional) gradient governs rheology
 - topography is isostatically compensated
- Low core density implies strong hydration (2400 kg/m^3)
 - late accretion
- OR
 - early efficient heat transfer due to hydrothermal circulation
- Early formation of subsurface ocean
- No ice-dominated shell at present day